

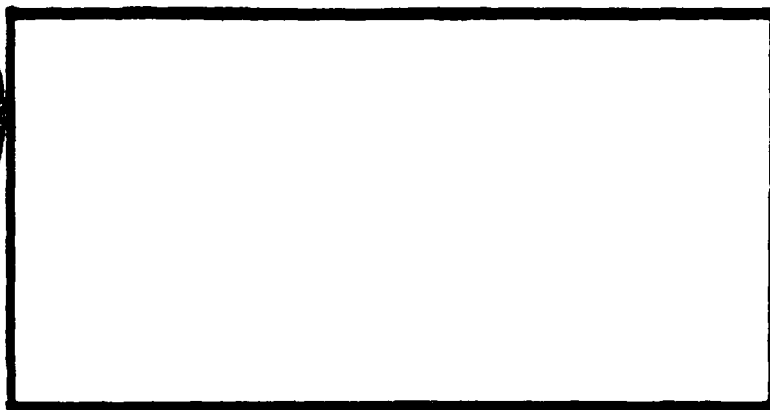
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Location and Routing of
the Defense Courier Service
Aerial Network

THESIS

Steven F. Baker
Captain, USAF

AFIT/GOR/ENS/91M-1

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Location and Routing of
the Defense Courier Service
Aerial Network

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Operations Research

Steven F. Baker, B.S.
Captain, USAF
March 1991

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Preface

Depot location and routing of delivery vehicles is a longstanding application of Operations Research techniques. Although the field is replete with optimizing algorithms which theoretically solve such problems, a more practical approach is dictated by the limitations of computing power. Consequently, alternate methodologies are developed which are feasible by modern computer standards, but which sacrifice solution accuracy by various amounts. This study applies several of the theoretical and practical algorithms with the goal of improving the Defense Courier Service aerial network.

During the course of the research I discovered that there were many experts in the field who were more than willing to offer their assistance. Major Mike Ackley and Capt Keith Ware of the MAC Command Analysis Group (HQ MAC XPY) were two such individuals. Their knowledge and insights of the DCS problem were key to the success of my effort.

In addition to the fine support I received from HQ MAC, as well as DCS itself, I am indebted to my advisor, Dr Yupo Chan. His ability to listen, counsel, and direct (when necessary) makes him an outstanding educator and researcher.

Throughout the research, my sanity was maintained with the loving support of my wife, Donna, and daughters, Kelly and Stacy. I hope that I may again provide them with the time that was formerly consumed by this study.

The current war in the Persian Gulf puts all defense oriented research in perspective. It is for the American soldier that all our efforts must be directed, and I hope this research ultimately makes contribution to that end. I salute all those currently defending our freedom.

Steven F. Baker

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Abstract

This study extends work done by the Military Airlift Command's Analysis Group on reducing the operating costs of the Defense Courier Service aerial network. The study's primary focus is to minimize those costs by varying the number and location of servicing depots, and the routes flown from those depots.

The theoretical algorithm used in the methodology is an expansion of Laporte's (1986) formulation of the multiple depot multiple travelling salesmen facility-location problem. Multiple servicing frequency is addressed by clustering co-located demands with Kulkarni's (1985) subtour breaking constraint. Vehicle range is considered by redressing a shortfall of the subtour breaking constraint, which was noted by Brodie (1988). The formulation is used as a validation of a system wide solution heuristic, since exact solution is beyond the range of current computing.

The solution heuristic is a combination of the minimum spanning forest (Prim and Dijkstra) and the Clark-Wright method. The spanning forest is used for depot location and partitioning, while the Clarke-Wright computes the routes flown from the depots to their assigned service points. The heuristic is suboptimal by 3.3% on average in six validation runs, with no run greater than 15.25% worse

than optimal. The results indicate several depots may be closed without large increase of system mileage.

LOCATION AND ROUTING OF
THE DEFENSE COURIER SERVICE
AERIAL NETWORK

Chapter I. Introduction and Background

The Defense Courier Service (DCS) is responsible for the transportation of classified material between Department of Defense installations. Some of this material has a low level of classification and may be carried by the US Postal Service. Some material is quite large and must be hauled by either cargo aircraft or truck. Much of the material, however, is small package size. Frequently, it is also too sensitive for ordinary postal procedure. The DCS has organized a secure network for the transportation of this material.

According to LTC Hughes of the HQ MAC command analysis group, the current DCS distribution network includes over 200 CONUS locations, most of which are serviced by aircraft. LTC Hughes further stated that the network is similar to a multiple "hub and spoke" system used by the nation's commercial airlines. The system also extends to overseas locations. Because classified material is generated at all the sites, the system is two-way. Most of

the individual sites are served by contracted small aircraft, which transport the material to a regional hub. The hubs serve as a secure transshipment center to United Parcel Service (UPS) aircraft, which move the accumulated cargo to another regional hub near the material's destination. The link is completed when another contracted general aviation contract aircraft delivers the material to its final destination. The major exceptions to this system are two east coast regional centers which are served by truck from the Washington DC area, a regional center (14).

Specific Problem

Over the years, the aerial portion of the DCS route structure has grown incrementally to 12 regional hubs serving 169 additional sites (1). Such a piecemeal growth pattern has resulted in a less than optimal route structure, though many of the current policies are sound. The DCS is satisfied with the current system of the UPS trunk carrier serving secure transshipment hubs which, in turn, supply the sites through general aviation aircraft. The current security, frequency of service, and capacity of the system components are adequate and need not be changed. Given these constraints, analysis of the current routes flown and hub locations will certainly indicate potential for overall cost reduction. This research explores the possibility of system

cost reduction by reducing the number of depots, altering depot locations, and changing the routes flown.

The costs associated with the aerial DCS network can be broken into 3 categories: 1) trunk cost fees paid to UPS; 2) payroll and other overhead associated with maintaining the regional hubs; and 3) contract costs to the general aviation carriers. Each of these three cost categories plays a major role in the route structure.

UPS charges the government a flat rate of 45 cents per pound of freight carried within its route system (18). This cost implies that there is no incentive in locating hubs close to each other, as they are separated by identical cost, regardless of the intervening distance. It also forces all hubs to be situated at locations served by UPS. Regarding the latter point, the DCS has stipulated that only military installations should be considered as potential hubs for security reasons (19). This constraint considerably reduces the number of candidate depots when combined with the UPS servicing requirement. The special government flat rate also reduces the study's scope, since trunking costs will not vary much regardless of number and location of depots.

Total hub operating costs vary with the number of hubs in the system, and the traffic through each hub. Clearly, adding more hubs will reduce the mileage flown by the small aircraft, but may adversely affect the economies

of scale associated with fewer but larger hub operations. Currently, there are 12 hubs, with yearly operating budgets (excluding contract costs) averaging \$718,000 (24). Though current depot operating costs are explored in Chapter III, varied regional and relocation expenses make the estimation of hub costs associated with a future network beyond the scope of this research.

The general aviation contractors are paid by the mile flown. The mileage rate is a function of many variables, including number of stops, total mileage, and number of bids received, as well as many other factors. A separate contract is negotiated each year for each depot, and the current agreements average between 1 and 2 dollars per mile (22). According to Capt Smith of DCS, security requirements generally necessitate that aircraft make only day-long missions. Furthermore, trip lengths are also limited by the FAA's 14 hour cap on the crew's duty day, and a ten flying hour maximum per crew, per day. Since the cargo is small package size, aircraft capacity is not a problem.

- Sites are serviced with established frequencies, generally
- either once or twice a week. These frequencies, though not beyond alteration, are currently satisfactory and are not to be varied in this study (19).

Since the UPS trunking cost is not largely affected by depot location and routing, and the depot costs involve significant regional factors which are best studied by DCS

itself, the primary focus of this research is the minimization of milage flown for a given number of depots. The methodology focuses on optimizing depot location and routing for a parametrically varied number of depots.

Though the primary effort of the research is focused on the scope described above, there are several additional considerations which will be addressed as warranted. According to Maj Perry of DCS, three of the hubs also serve as debarkation points for overseas cargo, effectively disqualifying them for potential relocation. Additionally, there are three priority routes which are flown from the Baltimore-Washington hub despite the higher costs associated with not providing service from the nearest depot. Finally, Maj Perry explained that there is no firm policy on the required servicing frequency of current depots, should they be relocated. He states that it is reasonable to use the frequency associated with the most served site within a given depot's route system (18).

Approach to the Problem

The research involves several phases. In order to determine an improved route structure, the current system must be examined in detail. Once familiarity with the structure is gained, mathematical formulation of the problem is used to gain further insight into practical solution methodologies, as well as validate the chosen technique.

Since DCS routing is a large problem, exact solution via mathematical programming is not possible using current algorithms and computers. Consequently, the problem must then be reformulated using heuristics, which will approximate an optimal system wide solution. Development of the the mathematical formulation as well as the appropriate heuristics is addressed in Chapters II and III.

System familiarity and data gathering are the central components to an understanding of the current DCS route structure. The HQ MAC analysis group has provided a large "head start" on data gathering, since they have already done considerable research on the problem. In addition to compiling the 181 locations and service frequencies, the analysis shop has completed a two stage series of recommendations to DCS (14). According to HQ MAC's report, the first stage involved reducing the current yearly system mileage of 1,550,395 without changing depots, depot assignments, or frequency of service. Their recommendation rearranged routes so as to fly only 1,454,609 miles per year, a 6.2% savings (13). The second stage recommended altering the depot assignments of some of the service sites. These changes resulted in a yearly mileage total of 1,400,070, or an additional 3.7% savings (13). Therefore, this research represents a third stage of MAC's analysis, in which the number of depots and their locations are varied in addition to the routing.

Summary

Although the DCS routing problem can basically be summarized as a multiple depot, multiple tour facility location and routing problem, it represents several challenges from a theoretical as well as a practical standpoint. Foremost among these is the problem size, which precludes exact solution by existing algorithms. This research focuses on tailoring existing mathematical algorithms to the specific problem, as well as developing a heuristic methodology for full scale solution.

Chapter II. Literature Review

Scope

The DCS aerial routing structure is a large network which schedules depot based aircraft to numerous demand locations, with subsequent return to base. This description squarely places the DCS network into the travelling salesman problem (TSP) category of Operations Research methodologies. Consequently, TSP literature is at the heart of the research background required for this study. While methodologies for solving TSP's are widespread, several specific formulations are applicable to the DCS aerial network. Those addressed in this review include: 1) the Vehicle Routing Problem (VRP); 2) modifications to the VRP; 3) the multiple depot multiple TSP; 4) TSP coefficient determination; and 5) heuristic solution techniques. These methodologies show great promise for adaptation to the DCS network.

The Vehicle Routing Problem

The Travelling Salesman Problem seeks the shortest route which connects a group of points (nodes) that begins and ends at the same point. One of the most comprehensive formulations of the TSP is the Vehicle Routing Problem as described by Chan and Rowell (6:13-14). The following list includes the notation used in this and subsequent formulations:

I = set of nodes
 i = departing node
 j = arriving node
 H = vehicle fleet
 h = individual vehicle
 d = arc distance
 x = 0,1 arc use indicator
 M = set of incident nodes
 N = set of eminent nodes
 f = amount of demand at a node
 V = vehicle capacity
 t = dwell time at a node
 U = tour time limit
 J = any node subset $\leq I$.

The formal VRP problem statement is:

$$\min \sum_{i \in I} \sum_{j \in I} \sum_{h \in H} d_{ij} x_{ij}^h \quad (1)$$

The first two constraints insure each point (except the depot) is served by only one vehicle:

$$\text{s.t. } \sum_{i \in I} \sum_{h \in H} x_{ij}^h = \begin{cases} |H| & \text{if } j=1 \\ 1 & \text{if } j=2,3,\dots,|I| \end{cases} \quad (2)$$

$$\sum_{j \in I} \sum_{h \in H} x_{ij}^h = \begin{cases} |H| & \text{if } i=1 \\ 1 & \text{if } i=2,3,\dots,|I| \end{cases} \quad (3)$$

The third constraint insures flow conservation:

$$\sum_{i \in M_p} x_{ip}^h - \sum_{j \in N_p} x_{pj}^h = 0 \quad \forall h, \forall p \in I \quad (4)$$

The fourth and fifth constraints restrict vehicle payload and range, respectively:

$$\sum_{i \in I} f_i \sum_{j \in I} x_{ij}^h \leq V_h \quad \forall h \quad (5)$$

$$\sum_{i \in I} t_i^h \sum_{j \in I} x_{ij}^h + \sum_{i \in I} \sum_{j \in I} d_{ij}^h x_{ij}^h \leq U_h \quad \forall h \quad (6)$$

Constraints six and seven insure the fleet size is not exceeded:

$$\sum_{j \in M_1} x_{1j}^h \leq 1 \quad \forall h \quad (7)$$

$$\sum_{i \in N_1} x_{i1}^h \leq 1 \quad \forall h \quad (8)$$

Finally, tours which do not originate at the depot (subtours) are prohibited:

$$\sum_{h \in H} \sum_{j \notin J} \sum_{i \in J} x_{ij}^h \geq 1 \quad \forall J \subseteq I \quad (9)$$

Though this formulation is very comprehensive, it is also somewhat cumbersome, and may be "streamlined" in many applications.

Vehicle Routing Problem Modifications

Merrill offers a considerably simplified multiple vehicle TSP (which eliminates the superscripts that delineate individual vehicles). The formulation combines the fleet size equations (7) and (8) into equations (2) and (3) above, and eliminates the payload and range considerations (16:2-3). Merrill also offers a much simpler subtour breaking method, which works for up to seven nodes. Merrill's primary effort, however, was focused on probabilistic demands within the network, a complication which the DCS network does not exhibit.

In an expanded discussion of the TSP, Chan and Rowell offer numerous ways of subtour breaking for problems with many nodes (6:12-15). Perhaps the most promising involves the use of "nodal potential" variables δ . These real variables force all connected nodes to be also connected with the depot in order to reduce their "potential" difference to 1:

$$\delta_i - \delta_j + |I| x_{ij} \leq |I| - 1 \quad \forall 1 \leq i \neq j \leq |I| \quad (10)$$

Chan and Rowell note work done by Kulkarni and Bhave which expand this constraint to restrict vehicle capacity and range:

$$\pi_i - \pi_j + Vx_{ij} \leq V - f_i \quad \forall K+1 \leq i \neq j \leq |I| \quad (11)$$

$$\sigma_i - \sigma_j + Ux_{ij} \leq U - d_{ij} \quad \forall K+1 \leq i \neq j \leq |I| \quad (12)$$

Here, the problem has been expanded to include K depots (discussed further below), and π and σ are capacity and range potentials respectively (6:15). Though the range restriction has been partially refuted by Brodie and Waters, both show promise after some modification (5:403-404).

One aspect of the multiple travelling salesmen problem which offers potential cost reduction is split delivery as described by Dror and Trudeau (11:139-145). Consider a vehicle which is close to a demand point, yet has insufficient capacity remaining to fully service the node. By partially serving the demand, other nearby vehicles may be enabled to use their remaining capacity to fully satisfy the node. Dror's algorithm is based on one and two node swaps among routes of a feasible solution. This has potential application to the DCS problem because the same node may require service from more than one vehicle. Such a split load in the DCS network is not capacity driven, but is required by the varying service frequencies of the demand sites.

Multiple Depot Problems

The complete DCS network involves the use of a trunk carrier (UPS) in order to supply the 12 regional depots. Though this research focuses on delivery from regional centers, the full nature of the network is best described by a hierarchical depot model. Such a model is formulated by Perl and Daskin, and described by Chan and Rowell (6:26-27). The hierarchical model consists of a single source which supplies regional depots by way of a trunk mode. From the regional centers, a second mode delivers the product to a final destination. The model is very comprehensive; consideration is given to trunking costs, regional operating costs, transshipment costs, and delivery costs. Because of its detail in describing a complex operation, the model formulation becomes quite large when even a small problem is considered.

Many delivery problems simply involve regional factories or distribution centers serving proximate demand locations. As described earlier, the DCS network is effectively such a problem, since the delivery costs to the centers (trunking costs) are independent of depot location. Laporte et al describe such a "multi-depot, multi-tour model" (15:293-302). In addition to those listed above, the following variables are used in Laporte's formulation:

c= fixed cost of a depot
b= fixed cost of a vehicle
m= number of vehicles at a
depot

J = subset of I including only
depots
 B = arbitrarily large constant
 p_i, P_i = lower and upper limits
on total depots
 t, T = lower and upper limits on
fleet size at a depot

The arcs are two-way and not capacitated by a binary
variable, therefore the problem is symmetric. The model
formulation is:

$$\min \sum_{i,j \in I} d_{ij} x_{ij} + \sum_{r \in J} (c_r y_r + b_r m_r) \quad (13)$$

$$\text{s.t. } \sum_{i < k} x_{ik} + \sum_{k < j} x_{kj} = 2 \quad k \in I-J \quad (14)$$

$$\sum_{i < r} x_{ir} + \sum_{r < j} x_{rj} = 2m_r \quad r \in J \quad (15)$$

$$\sum_{i \in L} \sum_{j \in L} x_{ij} \leq |L| - \frac{\sum f_i}{V} \quad L \subseteq I-J \quad (16)$$

$$x_{1112} + 3x_{1213} + x_{1314} \leq 4 \quad i_1, i_4 \in J \quad i_2, i_3 \in I-J \quad (17)$$

$$x_{1112} + x_{i(h-1)ih} + 2 \sum_{i,j \in \{i_2 \dots i(h-1)\}} x_{ij} \leq 2h-5 \quad h > 5 \quad (18)$$

$i_1, i_h \in J$
 $i_2 \dots i(h-1) \in I-J$

$$y_r \leq m_r \leq B y_r \quad r \in J \quad (19)$$

$$t \leq m_r \leq T \quad r \in J \quad (20)$$

$$p \leq y_r \leq P \quad r \in J \quad (21)$$

The objective function seeks to minimize the sum of
the leg costs, the depot overhead costs, and the aircraft
overhead costs. Therefore, for routes of equal length, a
single base with one aircraft is cheaper than multiple bases
with multiple aircraft. Constraint (14) specifies that all
nodes not used as a depot must be serviced exactly once. The
second constraint (15) insures that m vehicles travel from

their depot. Constraint (16) is a combined subtour breaking constraint and vehicle capacity constraint. Constraints (17) and (18) are chain barring constraints. They preclude a vehicle from originating at one depot and terminating at another. Constraint (19) requires that at least one vehicle is based only where depots are used. Equation (20) limits the number of vehicles at any depot, and (21) limits the total number of depots used.

One drawback of mathematical TSP formulations is that subtour breaking and chain barring constraints expand geometrically with problem size. Many such constraints are not binding on problem optimization however, and can be selectively eliminated. Chan offers such a constraint relaxation of the Laporte formulation described above (7:8-13). The process is iterative; it begins by comparing a known feasible (but not optimal) solution to a sub-problem solution which does not consider chain barring or subtour breaking. When such a sub-problem offers solution improvement, integer, subtour, and chain barring restrictions are added as necessary to induce sub-problem feasibility. If that sub-problem still offers improvement, it is stored as the best known and a new sub-problem is considered. The process continues until all sub-problems are considered.

Coefficient Determination

All of the vehicle routing problems described above require usable data regarding inter-network distances. Most of the formulations also simultaneously require fixed and variable costs for both depots and aircraft. Some research is warranted on transforming location data into distance information, as well as the factors which affect depot operating costs.

Transforming the latitudes and longitudes of two locations into inter-nodal distance is accomplished by the great circle distance formula provided in the Air Force Manual of Air Navigation (10:23-4):

$$D = 60\cos^{-1}[\sin(\text{lat}_1)\sin(\text{lat}_2) + \cos(\text{lat}_1)\cos(\text{lat}_2)\cos(\text{long}_2 - \text{long}_1)] \quad (22)$$

Here, lat and long denote latitude and longitude respectively, and distance (D) is given in nautical miles. Since a statute mile (used exclusively in this research) equals 5280 feet, and a nautical mile equals 6076 feet, the conversion is trivial.

Although cost evaluation of individual depots is beyond the scope of this research, relevant background is given by Corbett (9:25-39). Central to that research is the analysis of payroll and O&M costs of the southwestern depots of the DCS. While the research notes that the depots operate with some inefficiency, it finds that the basic DCS structure is sound.

Heuristic Solution Techniques

For large problems, the methodologies previously described become unusable. The constraints quickly become so numerous that the processing time becomes prohibitive. Consequently, heuristics have been developed to yield approximate solutions to large TSP's. The space filling curve, sweep, spanning tree, and Clarke-Wright are all heuristic methodologies which relate to travelling salesman problems and their variants.

Space Filling Curves. Bartholdi and Platzman describe the space filling curve (SFC) as a curve of unit length which connects a given set of sub-squares within a region (2:121-125). The central operation of the curve is to join a point with its immediate neighbors before proceeding to the next subregion. Each "neighborhood" is defined by repeated division of the entire region into 4 smaller and equally sized regions. The division continues until all points of interest (in this case, network nodes) occupy a square of their own. Figure 1 illustrates this. Once the

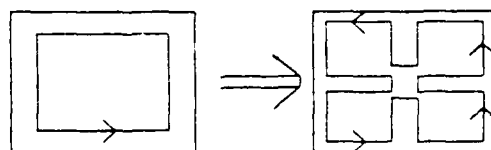


Figure 1. Space Filling Curves. Reprinted from (2:123)

space filling is complete, the points are assigned a value between 0 and 1, as specified by their position on the unit

curve. The order of points determines the vehicle's route. Bartholdi and Platzman claim solution accuracy to be no worse than 25 percent from optimal, and Merrill produced results averaging 4.5 percent (16:10).

The space filling curve may be used to solve problems other than the single TSP. In several works, Bartholdi and Platzman offer numerous such applications. Vehicle assignment to particular demand nodes can be formulated with the SFC (3:298), which applies space filling to a multiple TSP. In the same reference, multiple depot location is addressed. By segmenting the elongated curve into equally spaced portions, demand points are assigned to the potential depot location which is nearest the center of the segment. Alternately, segmenting and depot location may be done by placing a depot at intervals defined by equal number of demand points (3:298). Both of these methods are very simple, though they completely ignore natural clusters of demands which may occur along the curve. Even so, the multiple depot extension of the SFC make it potentially useful in solving the DCS problem.

Sweep Heuristic. Vehicle range limitation for a single depot is addressed by Teodorovic's description of the sweep heuristic (21:138-141). This heuristic plots the network on polar coordinates, with the depot located at the origin. An arbitrary starting demand point is chosen, which is point 1 in Figure 2. In this case, the heuristic sweeps

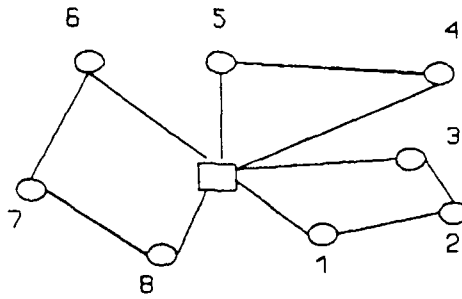


Figure 2. The Sweep Heuristic

counterclockwise through points 2 and 3, checking for range limitation prior to moving on. At point 3, the heuristic forces a return to the depot because proceeding to point 4 would exceed vehicle range. A new tour includes points 4 and 5, but proceeds back to the depot in lieu of exceeding vehicle range. The remaining points are added similarly until the sweep returns to point 1. The heuristic is simple, yet could be used to address aircraft range in the DCS aerial network.

Spanning Trees. A minimum spanning tree (MST) connects every point of a network to every other point with a minimum arc length. The name of the method springs from the resemblance of this collection of nodes and arcs to the branches of a tree. Prim and Dijkstra devised similar methods for MST construction; the latter is described by Syslo (20:259-265). Prim's algorithm begins at a seed (or depot) node and selects the least cost arc which includes an additional node into the "tree." At first this is simply the nearest neighbor to the seed. Thereafter, the nearest

unconnected neighbor to any node within the current tree is selected. At each iteration, the total arc length from the seed to the most current inclusion is added to the total network cost. Syslo also offers a PASCAL coding of Prim's algorithm which demonstrates the simplicity of MST construction (20:263-264).

A heuristic which transforms an MST into a travelling salesman problem is described by Nemhauser & Wolsey (17:475-482). The heuristic operates by doubling each of the arcs of an MST, then selectively eliminating those which cause node repetition along a continuous path. This formulation implies a relationship between the minimal spanning tree of a network and a suitable travelling salesman counterpart.

The connection between a network's MST and an efficient TSP tour is exploited by Ware in numerous applications within the Military Airlift Command's analysis group (23). One such application is the extension of the MST to include a forest, or many independent spanning trees within a system of nodes. In the minimal spanning forest, connecting arcs are grown from many seed nodes until every node is included in exactly one tree (23). This formulation has dual advantages: 1) demand points are assigned to depots; and 2) the MST algorithm which Nemhauser describes may be applied.

Clarke-Wright Method. Once demand nodes are assigned to depots, the DCS problem becomes an extension of the single depot multiple travelling salesmen problem. Several heuristic algorithms exist which solve such a formulation. One such formulation which shows promise for dealing with the DCS considerations of range and multiple frequency servicing is the Clarke-Wright algorithm. Originally described in 1964 (8:568-581), the Clarke-Wright algorithm initializes by assigning a separate "out-and-back" tour from the depot to each demand point. It iterates by combining the tours which offer the greatest savings as computed by the equation:

$$S_{ij} = D_{i1} + D_{j1} - D_{ij} \quad (23)$$

In this equation, the savings S equals the combined cost of travel to the depot from both nodes i and j , minus the cost of travel between nodes. This makes sense intuitively, as returning to the depot between proximate tasks can waste nearly an entire round trip from the depot. The algorithm terminates when no additional savings may be made, either through demand point exhaustion or vehicle capacity. Though the DCS problem is not restricted by vehicle capacity, range considerations could potentially be incorporated into the algorithm.

Beltrami and Bodin discuss the use of the Clarke-Wright algorithm for a network involving multiple servicing frequencies (4:406-427). In their discussion, New York City

garbage trucks are routed to locations with varying service frequencies using a modified Clarke-Wright algorithm. Though the detailed formulation is not given, the general procedure is discussed, which indicates usefulness to the DCS methodology.

Modifications to the Clarke-Wright algorithm are also discussed at length by Golden (12:113-148). Of particular note is his discussion of a multiple depot formulation. Unfortunately, the formulation includes only fixed depots, and does not iterate potential depot sites. Such a formulation could still be useful to the DCS solution, but only when a small number of iterations are required.

Summary

There is much literature which is both current and applicable to the DCS aerial network. Mathematical programming algorithms are available which solve problems which are virtually identical to courier routing, size being the only major difference. Heuristic algorithms are available which solve larger problems with reduced, but acceptable accuracy for many applications. These two areas of Operations Research provide the foundation for the research reported in this thesis. The remainder of the study is based on this foundation.

Chapter III. Methodology

Overview

The methodology outlined in this chapter is divided into two portions. First, a mathematical programming algorithm is developed which considers the DCS aerial network peculiarities. As stated earlier, such an approach is not applicable for solution of the full problem, though is useful from the standpoint of validation and analytical rigor. Second, a dual heuristic strategy is developed which: 1) approximates the optimal depot locations; 2) assigns demand locations to one of the depots; and 3) develops routing of aircraft between demand nodes and their depots. Together, the formulations provide for either redesign or modification of the DCS routing structure, as well as a reduced scale validation of results.

Mathematical Programming

The DCS aerial network most closely resembles the formulation given by Laporte, which is described in the previous chapter (equations 13-21). The formulation provides for multiple depots and multiple tours, though does not include provisions for range limitation or multiple servicing frequency. Additionally, some estimate of both fixed and variable depot cost is required for this model. Consequently, major foci of the DCS formulation involve

computation of suitable depot costs, and modifying Laporte's formulation for range and multiple servicing.

Depot Costs. Unlike many travelling salesman variants, Laporte's objective function seeks to minimize values which are not often thought of as being equivalent units. Furthermore, the DCS system involves numerous contracts spread throughout the CONUS, which implies that node and arc costs are dependent on numerous regional factors. Data is available on the current depot and per mile costs, but none exist for potential relocations. One way to approach the subordination of regional costs into the full network might be to assume that potential hubs would have equivalent costs to nearby existing hubs. Unfortunately, this method becomes rather uncertain when two existing hubs are proximate to a potential relocation site. The chosen method for regional smoothing of data is to predict potential depot and arc costs by using national data. Specifically, coefficients must be established for arc cost (d), depot fixed cost (c), and aircraft fixed cost (b). Since the demand servicing frequency is most often weekly, the model is formulated on a per week basis.

Contracts are awarded to small aircraft operators based on a negotiated per mile fee. As stated in Chapter I, this fee is a function of many variables including number of bidders, total miles flown, stops made, and operational complexity. Many of these factors are highly variable, but

are reasonably independent of the exact routing and depot location within the region. Using a national average might result in a slightly lower than optimal depot density where arc costs are relatively high (and vice versa), but the alternative of modelling so many variables makes the problem much less tractable. Therefore, a national average per mile arc cost of \$2.2287 (22) is used. This cost is not used directly in the formulation; rather it is used as a conversion factor between dollars and miles when incorporating depot costs. Note that the fee paid to the contractor includes all aircraft costs. This is very attractive as it assimilates the $b_r m_r$ terms of the objective function into the d_{ij} per mile coefficients. The d_{ij} terms are computed in statute miles, and the c_r terms are computed as described below and converted into a milage equivalent.

The depot overhead (including payroll and O&M costs) coefficients c_r , are a function of many disparate regional factors as well as more identifiable national ones. Appendix A shows the available data on the current number of total visits to demand points per two week period (labeled STA), number of yearly miles traveled by the contractor (MILES), number of sorties flown by the contractor (MSNS), and yearly depot overhead costs (COST). The three depots which are debarkation points for international traffic have disproportionally high operating costs, and are inappropriate for use in the O&M cost data set. The

remaining nine data points are analyzed using linear regression for coefficient determination.

Appendix A gives the results of the regressions done by SAS. Simple correlation indicates STA has the most promise for a good regression. That suspicion is borne out by scattergrams of the three candidate predictors. Though the most error is "captured" by the full model (as expected), the two predictor model including STA and MILES has a nearly identical R^2 of 0.2027. Unfortunately, both of these models have an unacceptably high p value associated with the F test. In each case, the null hypothesis of statistical model significance is rejected with greater than 50% confidence. The model with the most promise includes only the predictor STA. Its R^2 is 0.1525 and has a relatively low p value of 0.2988. A residual plot and Wilk-Shapiro test confirm normality of the error terms. While these results are hardly convincing of a strong regression relationship, they are a better measure than a raw average of depot cost, which completely ignores variable costs. It is also important to note that this calculation will ultimately be used only when a decision must be made between the cost of one additional depot versus the potential mileage saved. Since this decision is not included in the heuristic solution methodology, statistical skepticism of the depot cost model does not impact the validating power of the mathematical formulation, which is its primary goal.

Because the chosen model includes only the first order term STA, the size of a depot as measured by demand points served (per week) does not benefit from an economy of scale. Consequently, for a system with n nodes and I depots, the total per year depot cost (in thousands) is $I*b_0 + b_1*(n-I)$, where b_0 and b_1 are the regression lines's slope and intercept, respectively. Because of the linear relationship (which the scatterplot verifies), $b_1*(n-I)$ is constant regardless of how the demand is split among the depots, and may be added to the total cost after the optimal solution is reached. Appendix A shows that the intercept b_0 is \$392 thousand per year (or \$7538 per week), which corresponds to the fixed depot cost without the "stations serviced" constant. When converted to a statute mile cost equivalent, the weekly fixed cost is 3382 sm. Effectively, $b_0/(52*2.23) = c_r \quad \forall r \in (I-J)$, provided a constant 45.0 statute miles ($5220/[52*2.23]$) per demand serviced is added to the minimum weekly cost.

Since the regression attempt has severe statistical limitations, little value can be placed on the exact relative cost of depot overhead versus contracted operating costs. The regression does indicate that depots are relatively "expensive," since approximately 176,000 miles ($392,000/2.23$) must be saved in order for an additional depot's overhead to be justified. Additionally, depot construction costs are not considered, whose amortization

only increases the premium paid for potential depot sites. Although exact computation of relative depot costs is clearly beyond the scope of this research, system cost may be expressed by parametric weighting of operating versus depot costs. Stated in mathematical terms, Total cost = $L_1(\text{number of depots}) + L_2(\text{yearly mileage})$, where the L's are weighting variables that equate the two disparate expenditures. Using this approach, the best solution is offered for each of a given number of depots, whereupon the DCS may assess depot costs on a case by case basis.

Range Limitation. Both the Vehicle Routing Problem and Kulkarni formulations addressed in the previous chapter offer range limiting constraints which may be used in a travelling salesman problem formulation. Neither is exactly suited to Laporte's formulation, but Kulkarni's constraint has fewer disadvantages. The VRP range constraint forces the use of a vehicle superscript, which adds dimensionality and fixes number of vehicles. Consequently, Kulkarni's constraint is chosen and restated here for easy reference:

$$Ux_{ij} + \sigma_i - \sigma_j \leq U - d_{ij} \quad \forall |J+1| \leq i \neq j \leq |I| \quad (12)$$

The set $\{|J+1|, |J+2|, \dots, |I|\}$ represents the set of non-depot nodes; σ is an unrestricted variable associated with each node which indicates how much range capability remains in the associated tour (6:15). Note that the notation used here is the same as that used in the Laporte formulation (equations 13-21).

Careful inspection of the above equation reveals how σ serves as a tour "odometer." If an arc x_{ij} is used, its value is one, and the equation becomes:

$$U + \sigma_i - \sigma_j \leq U - d_{ij} \quad (23)$$

which can be simplified to:

$$\sigma_i + d_{ij} \leq \sigma_j \quad (24)$$

This states that the "odometer" variable associated with a demand node must be incremented by at least the distance separating it with the prior node on the tour. If the arc between two nodes is not used, the equation's right hand side becomes large relative to the left hand side, and the constraint is non binding.

Kulkarni's range equation requires x_{ij} to be distinct from x_{ji} . Otherwise, the incrementing from i to j is nondirectional, and a running total of milage is not forced. This complicates Laporte's heretofore symmetrical formulation by nearly doubling the number of variables, as well as forcing more rigorous conservation of flow equations. Specifically, equations (14) and (15) of the Laporte formulation become:

$$\sum_{i \in I} x_{ij} = \begin{cases} m_i & \text{for } j \in J \\ 1 & \text{for } j \in I-J \end{cases} \quad (25)$$

$$\sum_{i \in J} x_{ij} = \begin{cases} m_i & \text{for } i \in J \\ 1 & \text{for } i \in I-J \end{cases} \quad (26)$$

Additionally, the chain barring constraints must be altered to reflect the asymmetric formulation. The alternative to this approach is to ignore range considerations, or revert

to the vehicle routing problem formulation. Resorting to an asymmetric formulation remains preferable to either of these options.

The other major problem with incorporating Kulkarni's equation into the DCS problem formulation is that it ignores distance to and from the depot, which makes it incomplete. From the discussion above, it is clear that the σ associated with the first demand point on a tour should equal the distance from the depot. Additionally, the distance from the last node prior to returning to the depot cannot exceed the remaining range of the vehicle. Consequently, two constraints are added to redress Kulkarni's omission:

$$d_{ij} x_{ij} \leq \sigma_j \quad \forall 1 \leq i \leq |J| \quad \forall |J|+1 \leq j \leq |I| \quad (27)$$

$$d_{ji} x_{ji} + \sigma_j \leq U \quad \forall 1 \leq i \leq |J| \quad \forall |J|+1 \leq j \leq |I| \quad (28)$$

These equations, when used in conjunction with Kulkarni's, sufficiently restrict range.

By strictest definition, the DCS problem is not restricted by range, but by either the crew's duty day limitation of 14 hours, or by the less restrictive ten hour flying time limitation. According to Capt. Smith of DCS, 45 minutes is allocated at each stop for preflight and package delivery. Additionally, when circuitous routing and terminal procedures are considered, the aircraft travel at 200 statute miles per hour (19). Thus, the effective range of the aircraft is 2800 sm (14 hrs * 200 sm/hr), and the "range

cost" per stop is effectively 150 miles ($200 \text{ sm/hr} * .75 \text{ hr/stop}$). Prudence dictates that an error margin be added to these calculations, so Capt. Smith feels that no trip should be scheduled to last more than 13 hours, which corresponds to 2600 statute miles (19). Of course, the computed mileage between nodes must include 150 miles of "dwell time" in order to properly account for range considerations. This 150 mile cost per arc should be subtracted from the optimized cost after the program is completed.

Servicing Frequency. The most obvious way to allow for different servicing frequencies is to relax the binary mixed integer program into a simple mixed integer program. This would allow an arc flow greater than one, which permits a node to be served more than once. Because of the subtour breaking constraint (12), such a repeat servicing would have to occur on separate tours, lest a cycle occur which does not include the depot. This reformulation of equations (25) and (26) (conservation of flow) sets the right hand side equal to s_i or s_j for $i \in I-J$ and $j \in I-J$, respectively. S in this case equals the number of required servicings in a given period. Unfortunately, this prescription has one significant drawback; the "odometer" variables σ in equation (12) would no longer be multiplied by a binary variable, and would thus not record accurate "mileage."

Another method of forcing multiple servicing of a demand node is to redefine that node as a group of co-

located nodes, between which no arcs exist. Such a scheme allows the formulation to remain a binary one (except for the σ 's), since each node of the group requires one and only one servicing. One problem remains with this formulation. Theoretically, a path can visit one node of a collocated group, subsequently visit an adjacent node outside the group, and return to another node within the group. Since these visits all occur on the same tour, such a scenario does not conform with the intent of forcing multiple visits by different tours (conceivably at different times). To force all visits within a node group to occur via different tours, all nodes of a group are assigned only one "odometer" variable (σ). As before, this prohibits a tour from servicing any grouping of nodes more than once, effectively forcing as many tours as there are nodes into a given group. Thus, Kulkarni's constraint serves the DCS model by forcing multiple servicing, as well as subtour breaking and range limitation.

Full Mathematical Model. The complete DCS aerial network mathematical model is stated below in its entirety. Note that most of the equations have already been stated, and all bear close resemblance to previous equations:

I = set of all nodes
 d = statute mile distance + 150
 x = 0,1 arc use indicator
 U = vehicle range
 σ = unrestricted "odometer" variable
 c = fixed cost of a depot
 m = number of vehicles at a depot

J = subset of I including only
depots
 B = arbitrarily large constant
 p_i, P_i = lower and upper limits
on total depots
 t, T = lower and upper limits on
fleet size at a depot

$$\min \sum_{i,j \in I} d_{ij} x_{ij} + \sum_{r \in J} c_r y_r \quad (29)$$

$$\text{s.t.} \quad \sum_{i \in I} x_{ij} = \begin{cases} m_j & \text{for } j \in J \\ 1 & \text{for } j \in I-J \end{cases} \quad (25)$$

$$\sum_{i \in J} x_{ij} = \begin{cases} m_i & \text{for } i \in J \\ 1 & \text{for } i \in I-J \end{cases} \quad (26)$$

$$Ux_{ij} + \sigma_i - \sigma_j \leq U - d_{ij} \quad \forall |J+1| \leq i \neq j \leq |I| \quad (12)$$

$$d_{ij} x_{ij} \leq \sigma_j \quad \forall 1 \leq i \leq |J| \quad \forall |J+1| \leq j \leq |I| \quad (27)$$

$$d_{ji} x_{ij} + \sigma_j \leq U \quad \forall 1 \leq i \leq |J| \quad \forall |J+1| \leq j \leq |I| \quad (28)$$

$$x_{i1i2} + x_{i2i1} + 3(x_{i2i3} + x_{i3i2}) + x_{i3i4} + x_{i4i3} \leq 4 \quad \substack{i1, i4 \in J \\ i2, i3 \in I-J} \quad (30)$$

$$\begin{aligned}
& x_{i1i2} + x_{i2i1} + x_{i(h-1)ih} + x_{ihi(h-1)} \\
& + 2 \sum_{i,j \in \{i2 \dots i(h-1)\}} x_{ij} \leq 2h-5 \quad \substack{h > 5 \\ i1, ih \in J \\ i2 \dots i(h-1) \in I-J} \quad (31)
\end{aligned}$$

$$y_r \leq m_r \leq B y_r \quad r \in J \quad (19)$$

$$t \leq m_r \leq T \quad r \in J \quad (20)$$

$$p \leq y_r \leq P \quad r \in J \quad (21)$$

The above model may be input into any mixed integer
algorithm and serves as a reduced scale validation of the
heuristics described in the next section.

Heuristic Methodology Selection

The literature review suggests three possible
methodologies for solving the full-scale DCS network

problem. Space filling curve (SFC) heuristics offer simplicity and a combined ability to accomplish both the depot location and routing aspects of the problem. The minimum spanning tree (MST) formulation (and the minimum spanning forest (MSF) extension) is a bit more complex, but potentially offers improved depot location. The Clarke-Wright algorithm, though somewhat more complex than either the SFC or MSF approach, is very adaptable to the DCS range and multiple frequency extensions of the TSP. Unfortunately, none of these methods are without significant drawback. Space filling curves do not have a sophisticated approach to multiple tours, which is a critical factor in multiple servicing route design. The transformation of a spanning tree into a TSP is also poorly suited to multiple tours. The Clarke-Wright algorithm can only handle pre-defined depot locations, and requires too much time to iterate between all the potential DCS depot locations. Consequently, a hybrid approach to depot location and routing is appropriate.

Regarding depot location, speed is the chief advantage of space filling curves. The minimum spanning forest must iterate through all possible depot combinations before selecting the best single solution. However, the MSF is very well suited to grouping proximate demand points and depot sites, which is a shortcoming of the SFC. Additionally, a demand node may be weighted so as to reflect its required servicing frequency. In this way, depot

selection will tend to favor proximity to multiple frequency demand points. Finally, The MSF algorithm can be forced to preclude branches from becoming so long as to violate the range requirement. Because of these advantages, the MSF is selected as the depot location algorithm for the DCS solution heuristic.

Once the optimal forest is chosen, the individual trees indicate depot-demand assignments. Although Nemhauser's MST-TSP transformation heuristic seems appropriate for use here, its application to a multiple TSP is not provided in any of the reviewed literature. Moreover, the transformation from a MST to a TSP does not appear to readily lend itself to multiple tours. Since multiple tours are central to both the range and service frequency aspects of the DCS network, the MST-TSP transformation is not considered further. On the other hand, the Clarke-Wright heuristic does provide a workable incorporation of range and service frequency. For that reason, a combination minimum spanning forest and Clarke-Wright algorithm is chosen for solution of the DCS location-routing problem. Examples of the codes used are included in Appendix B, as well as the diskette included with this document. They should be referenced while reading the next two sections.

Minimum Spanning Forest Coding

As mentioned in Chapter II, Prim's spanning tree algorithm successively finds the shortest arc which adds another node into the current collection of nodes and arcs. The spanning forest expands this idea to several unconnected node-arc collections. The algorithm is a modified nearest neighbor heuristic, and the procedure for forest selection is as follows:

1. Select a combination of depots for branching. Define this set as the nodes currently included in the forest.
2. Admit the nearest node to the current forest unless the new branch connects that node to a depot which is greater than 1000 miles away.
3. Repeat step 2 until all nodes are included in the forest. Save as the best solution if the weighted distance is the smallest yet found.
4. Repeat step 1 until all combinations of depots have been explored.

The FORTRAN coding of this algorithm is straightforward. Initialization occurs by creating an inter-arc distance matrix, which is measured in statute miles and includes 150 miles per arc dwell time. Depot assignments are done first by declaring the fixed depots at Baltimore (KBWI), Kelly AFB (KSKF), and Travis AFB (KSUU). Thereafter, a succession of DO loops (FORTRAN syntax) define the current iteration of depot candidates. Initialization is completed by resetting the counters used during each iteration of depot combinations.

The main body of the code begins by pairing each demand node with its closest neighbor that is currently included in a collection (tree). Initially, this is simply the closest depot. Once each demand node is assigned a NEAR (variable name) tree branch, the current depot locations are defined as "collections of one," since no node-arc pairs have yet been formed. The program then searches for the smallest NEAR value, whose index corresponds to the next node to be included into a tree. Nodes whose inclusion would cause a potential tour to exceed 2000 miles (round trip distance to the depot) are disqualified. This is the upper bound on the distance to a service location, since the round trip flight time at this distance is approximately ten hours. Once a suitable candidate for inclusion into a tree is found, its distance to the tree's depot, times its service frequency rate is added to the total cost. Finally, the NEAR array is updated to determine if the proximity of each unattached node to the enlarged forest is changed.

The branch selection process continues until all nodes are included in exactly one tree. If the total cost is the best so far, it is stored along with the associated node-arc forest. A new initialization of depots occurs until all possible depot combinations are explored. The best solution is then written to an output file.

The main drawback of the spanning forest approach is the large number of iterations required to explore all

possible depot combinations. In addition to the current 12 depots, there are 18 CONUS locations where UPS provides service to a city near an active military airfield. Since only three of the depots are fixed, 27 choices remain from which to choose. In a problem which seeks 11 depots, the number of iterations required is over 2.2 million. The selection process requires considerable computer time.

Despite the daunting size of the depot selection process, the MSF coding is highly effective as it incorporates range and multiple frequency weighting. These advantages make it a critical part of the DCS solution heuristic.

Modified Clarke-Wright Coding

The original Clarke-Wright (CW) algorithm was designed as a multiple tour, vehicle capacity constrained heuristic for solving single depot TSPs (8:569). The DCS problem relaxes the vehicle capacity portion, but includes range and multiple frequency servicing. As with the mathematical programming approach, range is constrained by disallowing links on a tour which would cause the overall length to exceed 2600 sm. Also borrowed from the mathematical programming formulation is the concept of node clustering to simulate multiple demands. Both of these methods require keeping track of which tour each node is on,

which is the major extension of the CW algorithm used in this research. The procedure follows these steps:

1. Construct the savings matrix using equation (23).
2. Select the arc offering the greatest savings unless the new tour length would exceed range, or the new tour involves revisiting a cluster already served along the route.
3. Proceed until no further savings can be achieved due to the restrictions in step 2.

FORTTRAN implementation of this algorithm initializes by assigning a unique tour number to each node, except for clustered nodes, which are assigned one number per cluster. Each node is then assigned the number two, representing the number of connections with the depot it currently has. During the course of the run, this number is reduced to as low as zero, indicating that no further route consolidation can be considered using this node. Finally, the distance and savings matrices are computed, using equations (22) and (23), respectively.

The code's main body scans the savings matrix for the maximum value, which is chosen unless: 1) either of the nodes cannot further consolidate an arc; 2) consolidation would exceed range; or 3) the consolidation would revisit a cluster already included in the tour. The range and tour number arrays are then updated to include the most recent consolidation. This is a rather arcane piece of code, replete with buffer arrays and arrays used as indices for

matrices. The foundation lies in accurate updating of the tour number array (NC) of every node of a newly consolidated tour. This is accomplished by combining and then scanning the NCV matrix row for each of the newly combined nodes, which keeps track of the other nodes in the indexed node's tour. In turn, this information is copied into those nodes' NC and NCV arrays, which completes the update. Finally, the new arc is written and tallied into the total network cost. When no further consolidations are feasible, the total cost and remaining depot connections are written, and the run terminates.

Heuristic Summary

As noted earlier, depot location and routing for the DCS problem is a two part process, first involving an exhaustive search of location possibilities, then designing routes from those depots which conform to the DCS network constraints. As expected for any large network, the combined process involves considerable computer time, but promises to be quite flexible. Though the principal focus of this research is a long term relocation strategy, a more useful short term application is selection of a depot for closure as a cost cutting measure. It is this flexibility which will allow the combined heuristic to serve the DCS for the foreseeable future.

Chapter Summary

The mathematical program offered at the beginning of the chapter is a rigorous formulation of the problem which confronts the DCS location and routing analyst. The heuristic solution approach offered in the chapter's second half provides a medium by which those problems can be solved at a system sized level. The combination of the two methodologies offer not only a solution scheme, but a means by which to validate the results. The next chapter describes the outcome of that process.

Chapter IV. Results

Overview

This chapter focuses on validation of the heuristic methodology via mathematical programming, and solution of the DCS network by the verified heuristic. The validation portion consists of three separate problems of sharply reduced size. They are each solved to optimality using the modified Laporte formulation developed in Chapter III; those solutions in turn are used as performance measures of the approximated solution using the combined minimum spanning forest/Clarke-Wright (MSF/CW) heuristic. The chapter then describes the use of the heuristic to offer best known routings for a given number of depots (using the criteria for depot location given in chapter III). Finally, a near term restructuring of the network is presented which offers savings through depot closures without drastic system change.

Validation

The three "mini-networks" used for validation purposes consist of locations served by the DCS network. Since even regional DCS modelling is beyond the capability of current computers, the maximum number of locations considered is six. This allows for co-location of demand and potential depot sites, as well as multiple servicing demands

(recall that a demand frequency of 2 effectively requires 2 nodes within the formulation). Although the locations correspond to actual DCS service points, the servicing frequencies and depot suitability do not mimic reality, since those parameters are chosen to test various aspects of the code.

Since number of depots must be varied manually in the MSF/CW heuristic, two separate problems must be considered for each test case (each of the three regions offers two potential depot locations). Each region is first solved for optimality, which results in a single depot selection since depots are relatively expensive. A two depot case is forced after the results of the single case are known, and both cases are compared with the heuristic solution.

The Laporte algorithm is coded into MIP83, a PC-based mixed integer solver. Run times on an AT class microcomputer at 8 MHz (with math coprocessor) varied between 15 minutes and 6 hours, which is testament to the limitation of the algorithm to small problems. Samples of the input code as well as all of the output files are given in Appendix C and the accompanying diskette. Also included in Appendix C are the output files for all of the (test region) heuristic code runs.

Once the exact solution has been determined by the Laporte algorithm, the test region data are loaded into the

MSF code in order to select depots and assign demand locations to depots. The optimal forest is then broken into its component trees for input into the CW code. Thus, the validation process for each case consists of three steps: 1) exact solution by Laporte algorithm; 2) selection of heuristic forest by the MSF code; and 3) tour selection by the CW code, using the MSF results as input. Total system mileage is the measure of effectiveness used to evaluate the heuristic methodology.

Region 1. This test consists of several Northwest bases, including potential depots at McChord (TCM) and Travis (SUU), single demands at TCM, BOI, LMT, MUO, MUO, Klamath Falls

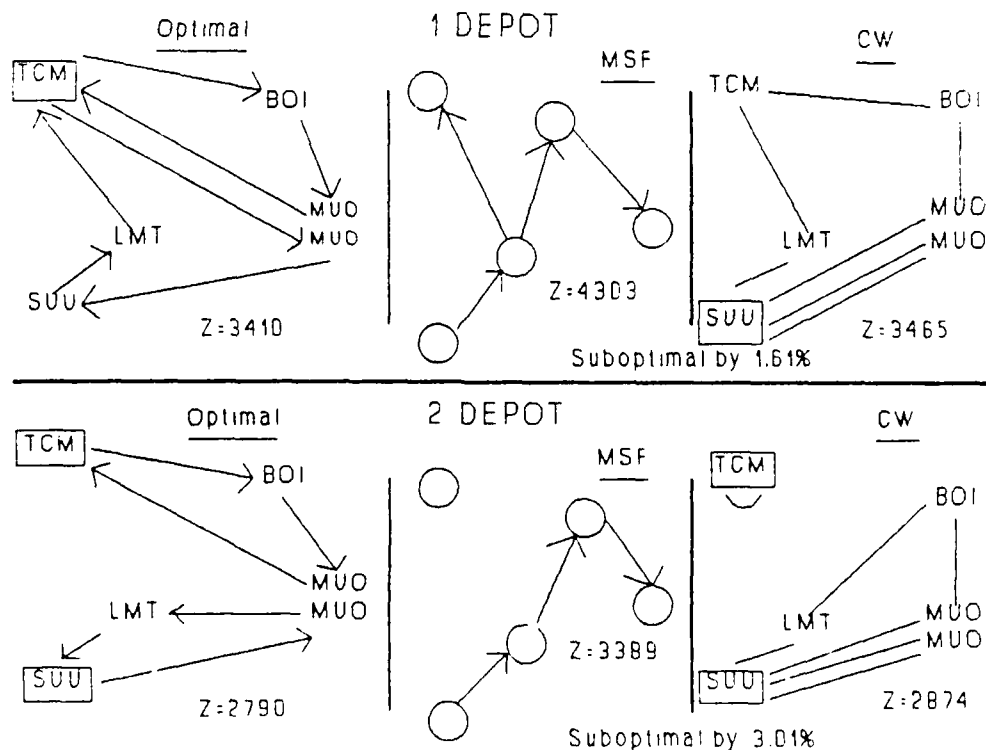


Figure 3. Validation Region 1

(LMT) and Boise (BOI), and a double frequency demand at Mountain Home (MUO). Figure 3 summarizes the various computer outputs. It is chosen because the geometry offers two nearly equal depot candidates from a visual inspection. It also forces at least two sorties since MUO must be visited twice. The graphics conventions for this and the ensuing routing figures depict the chosen depot within a box, and multiple servicing requirements by repeated station name (i.e. MUO written twice). The leftmost portion of the figure illustrates the optimal solution as delineated by Laporte's algorithm run using MIP83; the center portion depicts the Minimum Spanning Forest solution as computed by the code in Appendix B. The far right portion depicts the approximate solution as computed by the Clarke-Wright code and the depot-demand pairings given by the MSF. The objective function values are also given as a reference.

The results of this first validation run show the heuristic to be suboptimal by only 1.61% for the single depot case, and just 3.01% when two depots are forced. However, the MST heuristic chose SUU instead of the optimal TCM in the one depot case, and did not fully utilize TCM in the two depot instance. Fortunately, these deviations did not result in significant loss of overall performance.

Region 2. This validation includes six Midwest bases which all require only one servicing. The depot candidates are Offutt (OFF) and Wright-Patterson (FFO). The

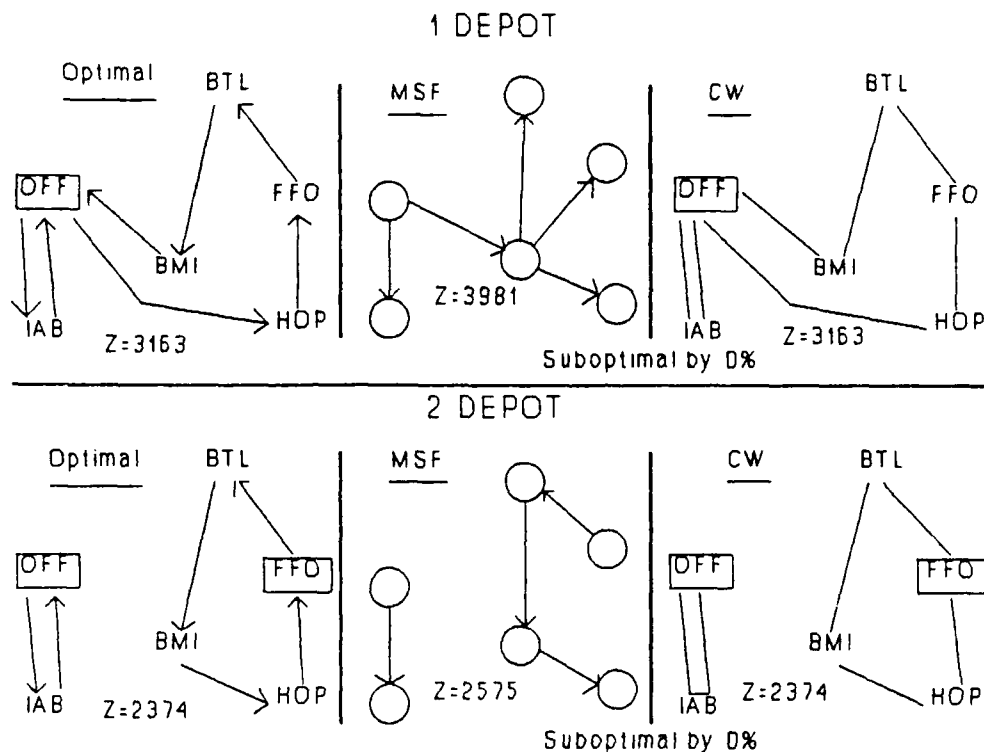


Figure 4. Validation Region 2

other bases requiring service are McConnell (IAB), Battle Creek (BTL), Bloomington IL (BMI), and Ft. Campbell (HOP). The demands are geographically distanced so as to exceed the maximum sortie range, thereby forcing at least two separate missions. Despite the proximity of more of the servicing locations to FFO, OFF is chosen for the single depot because of the remoteness of IAB. The MSF/CW heuristic is not fooled by this; it chooses the optimal solution in both the one and two depot cases. Additionally, none of the solutions include missions of excessive length, indicating that the code properly constrains range.

Region 3. This region consists of bases located in the Southeast with potential depots at Charleston (CHS) and

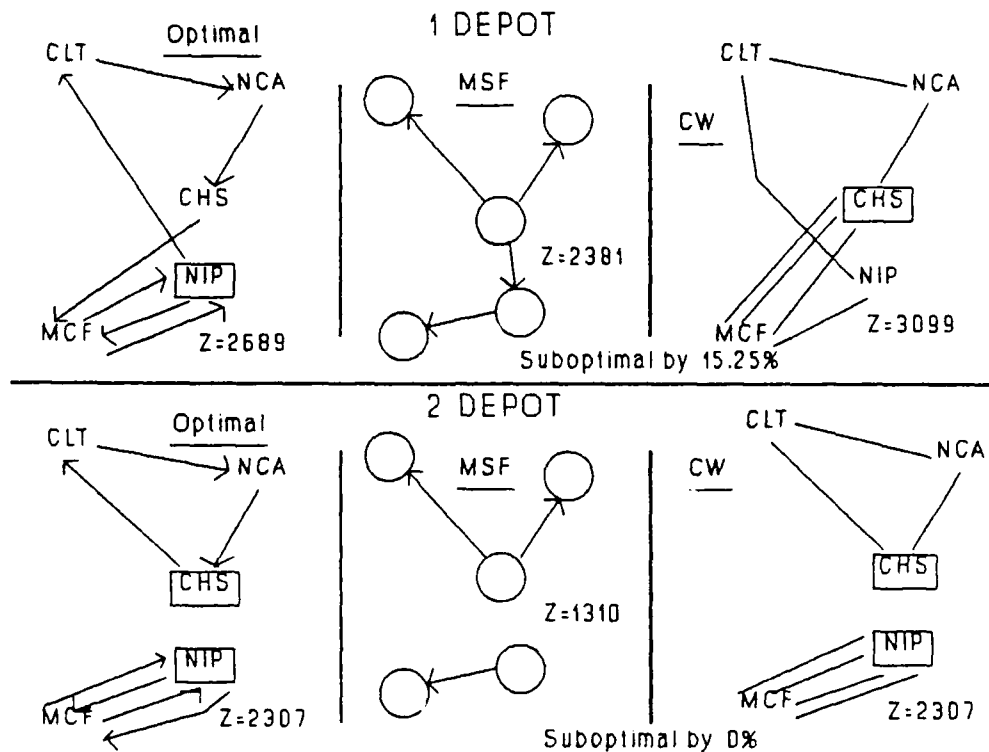


Figure 5. Validation Region 3

Jacksonville FL (NIP). Service must include the depot candidates as well as Charlotte (CLT), Jacksonville NC (NCA), and MacDill (MCF). The locations are chosen in order to force a choice between a depot with a proximate multiple servicing requirement (NIP serving MCF), and a depot nearby two single-service locations (CHS serving NCA and CLT). Although the optimal single depot solution selects CHS, the MSF forces a solution using NIP, which restricts the solution to 15.25% from optimal. This does not occur when a two-depot solution is forced; the heuristic replicates the optimal solution.

Validation Summary. The heuristic solution averages 3.32% from optimal for the six problems considered. The

range of error spans between 0% (three occurrences) and 15.25% (1 occurrence). Although an upper bound is not established by this method, one may be reasonably assured that other results would not be markedly worse than those produced by the runs, since the region geometry was purposely chosen to make location-routing selection difficult. Depot selection appears to be the weakest ability of the MSF/CW heuristic; both division of service among depots and routing within a depot system mimic the optimal with reasonable accuracy. Consequently, MSF/CW results produced on the full DCS network should be reasonable (within 15%), though some depot misplacement may occur. This characteristic may be ameliorated by serendipity; one of the strengths of parametrically varying the number of depots may well be the continued reselection of many of the same depots. Indeed, Ware of the MAC analysis group has found a robustness of depot selection in similar networks (23). If indeed this is true for the DCS network, greater confidence of these robust depots may be assumed. The next section addresses this aspect, as well as the entire MSF/CW heuristic solution of the DCS network.

MSF/CW Heuristic Solution

Since the MAC analysis group has already offered a restructuring of the DCS network using the 12 current depots, and since depots appear to be relatively expensive

entities, solutions offered in this research only consider fewer than the 12 current depots. To that end, the number of depots is varied between 11 and four; the latter figure proves to be infeasible due to inadequate aircraft range. At the outset of each iteration, the data set listed in Appendix D is input into the MSF code described in Chapter III. That set first lists the three unmovable depots, followed by the remaining 27 depot candidates and the 151 service-only locations. The data are arranged with the current depots first in order to award ties to those locations.

As stated earlier, the MSF code is computationally intense; in the case of the 11 depot run the code must find the best of "27 choose eight" forests, which is in excess of 2.2 million iterations. Fortunately, the number of possible combinations drops quickly as the required number of depots is reduced. The ten depot problem involves less than 900 thousand combinations, and the seven depot problem requires scarcely 17.5 thousand forests. All runs were made on a VAX 8550. The 11 depot problem required just over 2.7-CPU days. Each remaining problem was run in decreasing order of complexity and, predictably, took less than half the CPU time of its antecedent. Each CW run took nominal CPU time and most were accomplished on a microcomputer. The output of each MST and appropriate CW runs are given in Appendix E.

Once the best forest is chosen it is split into its component "trees," which are (in turn) input to the CW code. Since the frequency of service varies from every other month to six times per week, many of the "trees" have a different least occurring frequency, which corresponds to the smallest usable increment of time when computing the route structure. In other words, a depot which serves an every-other-month location must have its routes computed for two months before repetition, which cannot be directly compared with a depot whose least occurring service frequency is weekly. Another standardization measure is the subtraction of the 150 statute miles per leg which was added in order to restrict range. Each of these two computations is done manually and accompanies the CW output. Since many of the CW output files apply to several of the MSF runs, the output is only given the first time it is needed. The following is a summary of those runs.

11 Depot Model. The MSF computation finds that nine of the 11 depots chosen are current depots. Only Griffiss AFB (which is served by UPS at Syracuse), and Little Rock AFB (served by UPS at the adjacent city) are new to the system. The McChord AFB, Norfolk, and Denver depots have been deleted from the system. A graphic presentation of the MSF structure is given in Figure 6. The forest cost, though not physically representative of any network cost, is 279,481 statute miles. The inter-depot boundaries appear

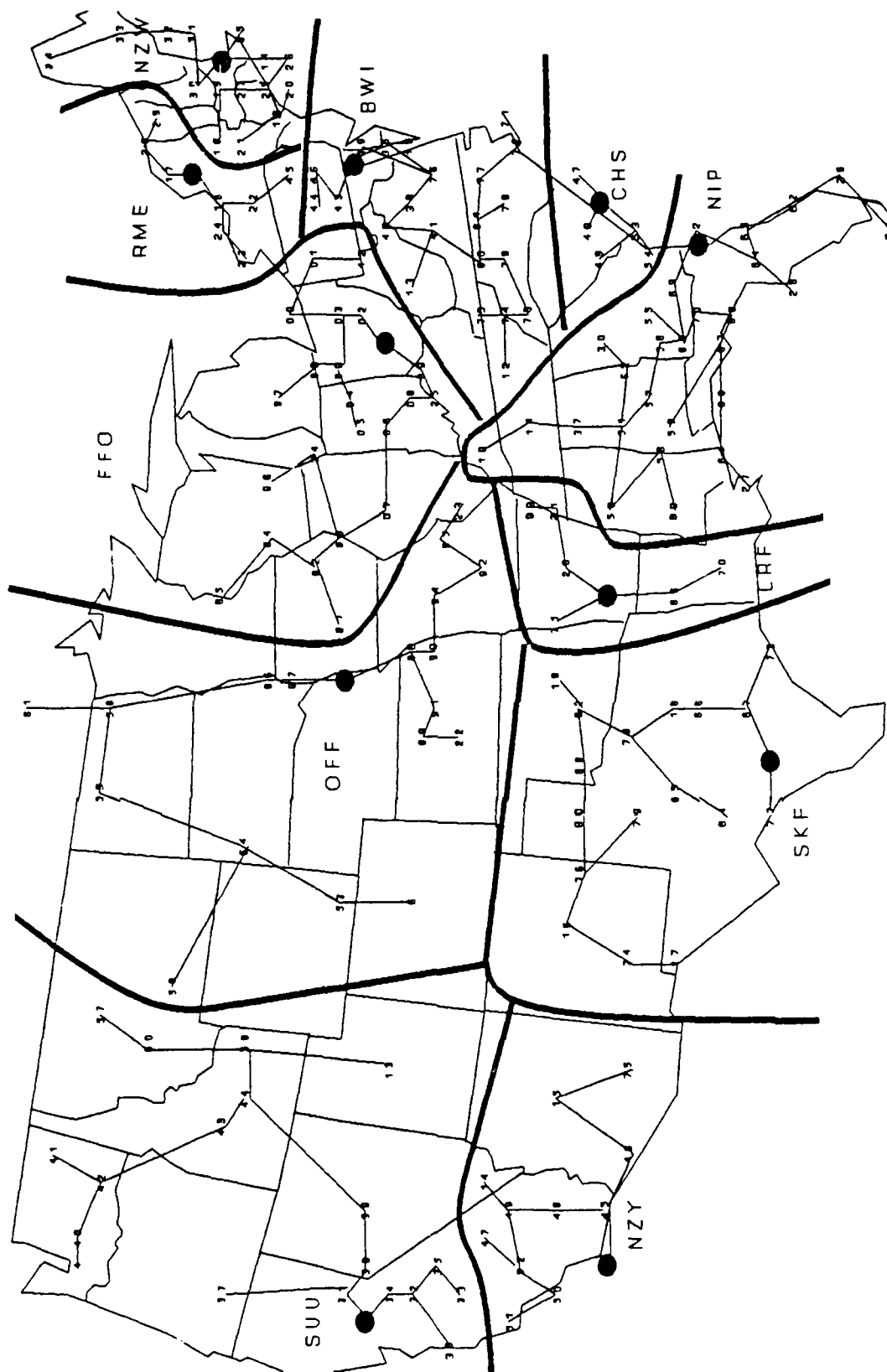


Figure 6. 11 Depot MSF

logical in nearly all locations, and even appear similar to many current boundaries. An unnatural association with one Montana location and the depot at Offutt exists, and is due to the range limitation of aircraft stationed at the Travis depot.

The combined total mileage flown is computed by the CW code to be 24,070 sm per week, or 1,251,640 sm per year. This compares very favorably with the current yearly mileage of 1,550,395 (13). It also compares well with MAC's stage two suggestion of 1,400,070 sm per year (13). Although many factors (addressed in the next chapter) must be considered before directly comparing these models with the current system, the results are, nonetheless, encouraging.

10-4 Depot Models. Each of the reduced depot models is similar to its predecessor model with regard to forest appearance. In all cases, the service stops of one depot are assimilated into a nearby depot, and the widowed depot is closed. This characteristic makes the new route mileage very simple, since only one depot's routes are changed (due to the inclusion of its former neighbor's service locations).

Table 1 lists the number of depots in each of the reduced models ("Depots"), the name of the eliminated depot ("Loss"), the assimilating depot ("Expand"), the yearly mileage cost, and the difference in mileage from the next larger system model.

Table 1.
Iterated Depot Closures

<u>Depots</u>	<u>Loss</u>	<u>Expand</u>	<u>Yearly Mileage</u>	<u>Mileage added</u>
10	NZY	SUU	1,275,924	24,284
9	LRF	NIP	1,332,344	56,420
8	CHS	BWI	1,360,424	28,080
7	RME	NZW	1,374,152	13,728
6	NZW	BWI	1,428,284	54,132
5	FFO	BWI	1,635,764	207,480

The only exception to the iterated depot closure routine is between the six and five depot models. Two of the service locations (DSM and MSP) of FFO are not within range of BWI, so the MSF attached those locations to the OFF tree. Limited range also precludes a system with less than 5 depots. Since three of the depots are fixed, a four depot model only allows one variable depot location. Significant voids exist in both the North-Central and Southeast CONUS, and a single depot cannot serve both regions. The MSF code notes this by assigning a very large penalty cost for infeasibility.

Depot Closure Sequence. Since depot closures appear to be events which affect only one other depot in the system, it is clear that the depots ought to be closed in an order where the mileage increase is always the least. In other words, there is little merit in merging North Island's routes into Travis' (at a yearly cost of 24,284 miles), when Griffiss' routes may be merged into Boston's for a lower yearly mileage addition (13,728). The fact that the MSF code does not shut down depots in this order shows some limitation of its effectiveness.

The inherent difference between a spanning forest and a travelling salesman route system is to blame for the less than optimal ordering of depot closures. When Appendix E is examined, the MSF objective function differentials are continuously increasing. Unfortunately, Table 1 testifies that this does not translate into a continuously increasing cost differential for the CW route structure. This discrepancy may be rectified by examination, however. Table 2, supported by the calculations at the end of Appendix E, accomplishes this reordering. As with Table 1, it uses the 11 Depot model (shown in Figure 6) as a starting point.

Table 2.
Improved Depot Closure Sequence

<u>Depots</u>	<u>Loss</u>	<u>Expand</u>	<u>Yearly Mileage</u>	<u>Mileage added</u>
10	RME	NZW	1,265,368	13,728
9	NZY	SUU	1,289,652	24,284
8	CHS	BWI	1,317,732	28,080
7	NZW	BWI	1,371,864	54,132
6	LRF	NIP	1,428,284	56,420
5	FFO	BWI	1,635,764	207,480

The order of depot closure stated in this table presents a more cost effective closure sequence, since the minimal incremental cost is added at each level.

The data in Table 2 are central to finding the optimal number of depots for the DCS network. The curved line in Figure 7 is a plot of these data, and it portrays the cost line formed by trading depot and operating (mileage) costs. The straight lines in Figure 7 are the budget lines (estimated, 90% upper, and 90% lower bounds)

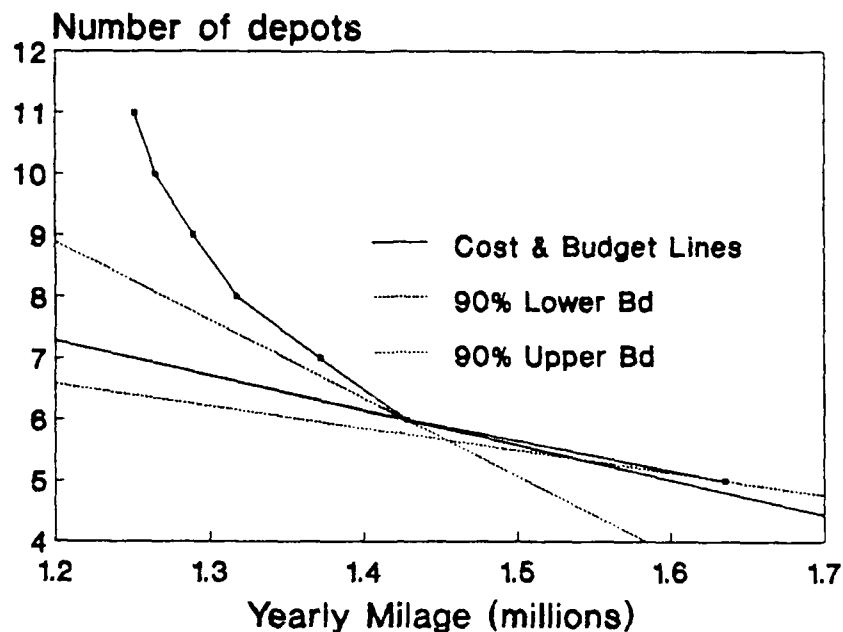


Figure 7. Depot Versus Operating Costs

computed in the regression done in Chapter III. The regressed slope of the estimated budget line is -5.681 , or 2.229 dollars per mile divided by $.392$ million dollars per depot (the negative sign accounts for the inverse relationship of depots and mileage). Budget estimation based on these coefficients must also include a constant term for the number of stations served, since the regression model incorporates that parameter. As caveated in Chapter III, these computations are more of an example than a statistically sound estimate, since: 1) the hypothesis test associated with the depot cost model is not convincing; and 2) the dollars per mile estimate is a nationwide average. However, based on these cost figures, a six depot system is optimal. Stated another way, the yearly mileage cost of a

depot in this model is $(3382 \times 52) = 175,864$ miles. Since the transition from six to five depots is the first reduction which exceeds that cost, the six depot network is the cheapest alternative.

Formal restatement of the depot versus mileage ($5 \leq \text{depots} \leq 11$) optimization for the DCS network is best done mathematically. :

$$\min \quad L_1 \text{ DEP} + L_2 \text{ SM} \quad (32)$$

$$\text{s.t.} \quad - 72.99 \text{ MSM} + 102.33 \leq \text{DEP} \quad (33)$$

$$- 41.19 \text{ MSM} + 62.13 \leq \text{DEP} \quad (34)$$

$$- 35.61 \text{ MSM} + 54.90 \leq \text{DEP} \quad (35)$$

$$- 18.47 \text{ MSM} + 32.34 \leq \text{DEP} \quad (36)$$

$$- 17.72 \text{ MSM} + 31.31 \leq \text{DEP} \quad (37)$$

$$- 4.82 \text{ MSM} + 12.86 \leq \text{DEP} \quad (38)$$

Here, DEP, SM, and MSM denote the number of depots, statute miles, and million statute miles per year, respectively; L_1 and L_2 equal their associated costs. Regional estimations of these coefficients by DCS will dictate the system optimal. finally, a constant term is included in the objective function in order to convert to a budget estimate.

Near-Term Recommendation

Since the methodology discussed so far calls for radical restructuring of the DCS aerial network, a near term solution is proposed which looks much more like the current structure. Notably, this proposal does not include any new

depots, and preserves the three "priority routes" between Baltimore and FFO, LFI, and HUA. This proposal is much more problem specific; it is consequently less theoretically rigorous.

Because the priority routes to Wright-Patt, Langley, and Huntsville are high-frequency events (six, six, and two times per week, respectively), there is considerable ability for aircraft flying these missions to also serve other locations along the route. Since these aircraft are, by definition, Baltimore based, all locations between BWI and the priority destinations are good candidates to be included in the BWI depot structure. Although the term "between" is somewhat ill-defined, use of the system map aids in approximating good potential enroute stops. Figure 8 shows the approximation used in this research; it is a combination of prior depot divisions and "eyeball estimation." Analytical selection is a clear topic for further research.

The number of depots is another variable which could be altered prior to final system selection. In this case, however, the MAC analysis group has already made recommendations regarding a 12 depot structure. Additionally, the proximity of the depot at Norfolk to the enlarged BWI depot (proposed here) makes NGU a good candidate for elimination. Finally, one other depot shall be eliminated in order to not replicate MAC's results in areas

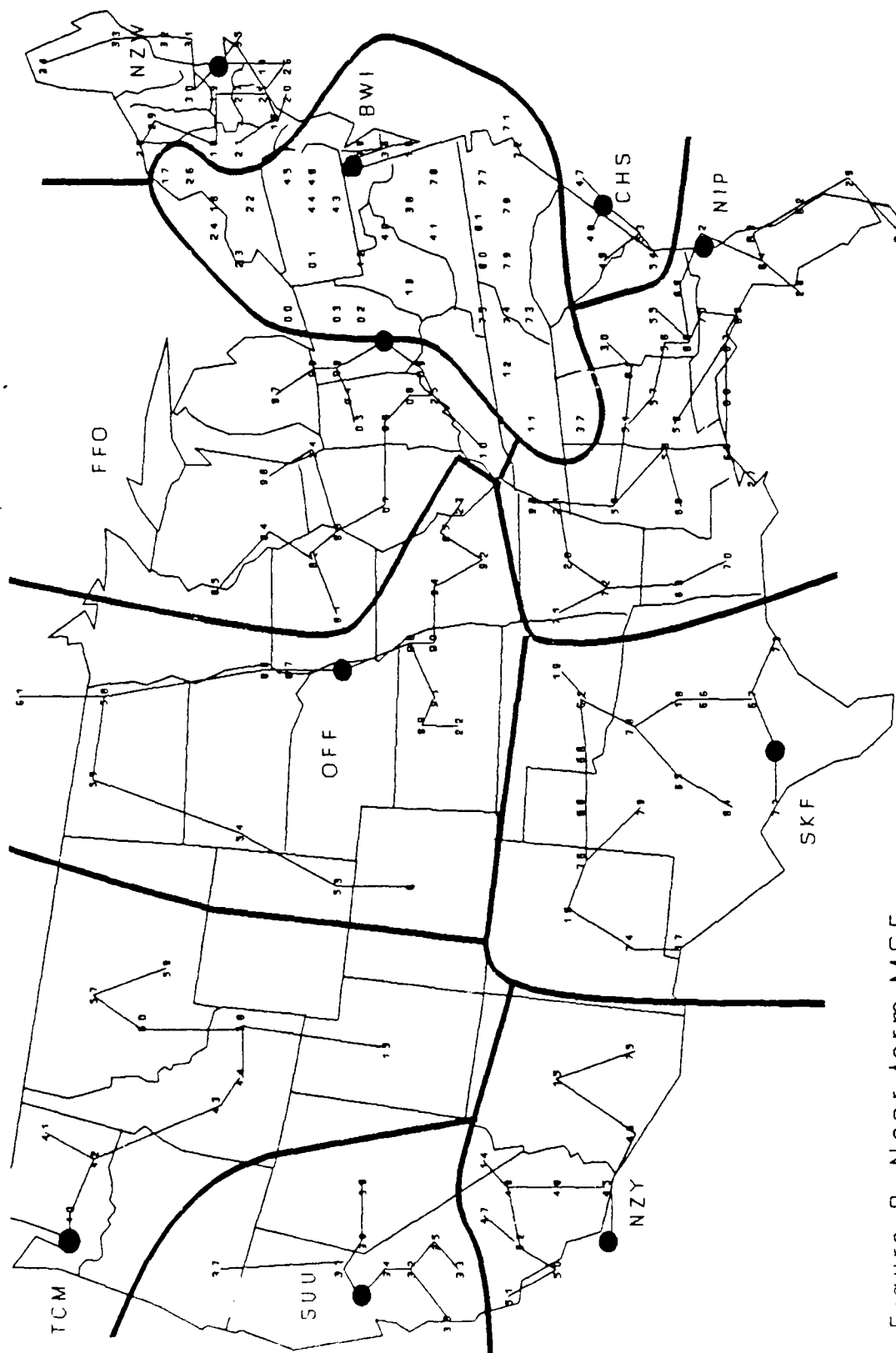


Figure 8. Near term MSF

outside the BWI region. Thus, a ten depot MSF/CW model is considered using the a priori BWI service locations.

In addition to the BWI exclusions, Figure 8 depicts the output MSF. The computer output for this and the associated CW runs are included in Appendix F. Accompanying the output is a full output interpretation of the routes.

The combined heuristic determines that Denver is the most eligible base for closure, based on route efficiency. The solution directs 1,448,148 miles per year without radical restructuring. This figure, while 48,000 miles per year above the 12 depot network offered by MAC, accomplishes the same level of service without the Denver or Norfolk depots. For that reason, the ten base option appears competitive, and should be considered if depot reduction is a priority.

Heuristic Summary

- The combined MSF/CW heuristic can be used to construct a DCS routing system that offers depot reduction
- without large mileage penalties. The combined solutions
 - range from 11 depots with 1.2 million yearly miles flown, to five depots with missions totaling 1.6 million yearly miles. The method is also flexible; the inputs are easily varied to accommodate short term network improvements. It appears to be well suited to DCS network analysis.

Chapter Summary

The formulation given by Laporte and modified in Chapter III is verified by integer programming using several test problems. Those problems are used in turn to validate the combined minimum spanning forest/Clarke-Wright heuristic developed in Chapter III. The validation uncovers heuristic errors ranging from zero to 15.25%. The weakest single aspect of the heuristic is its ability to distinguish between depots which offer similar degrees of network improvement. This is borne out in the analysis of DCS data. Fortunately, some of the error can be easily seen and subsequently reprioritized by hand calculation.

Usefulness of the validated heuristic is shown by the results which direct less yearly distance than is currently flown. The heuristic is flexible and can be used on the DCS network regardless of the degree of restructuring which is practical or desired. It leaves the decision maker with many attractive options.

Chapter V. Contributions and Conclusion

The purpose of this study as stated in Chapter I is to explore the possibility of system cost reduction by decreasing the number of depots, altering depot locations, and changing the routes flown. A methodology for the reduction of DCS network costs by these means has been developed and demonstrated in this research. Central to the study is the development of extensions to the multiple-depot, multiple travelling salesmen problem. These extensions encompass the theoretical problem as well as heuristic alterations that accommodate a specific set of range and servicing constraints. During the course of the research, several areas for future study have been uncovered, and provide for ample follow on research topics. Finally, the techniques used are shown to be an effective and flexible tool to DCS aerial network improvement analysis. This chapter summarizes these aspects of the research.

Mathematical Programming Extensions

Tailoring the well known Laporte formulation of the multiple-depot, multiple travelling salesmen problem is essential to rigorous mathematical statement of the DCS network. To that end, one key contribution of this research is the clustering of nodes to allow for multiple servicing

by different tours. The other primary contribution is the "shoring up" of the Kulkarni method of combined subtour breaking and range limitation. These two additions to the formulation are, however, performed at the cost of restating the formulation asymmetrically. Despite this added complexity, the extended formulation has applications well beyond the specific DCS problem, since range and servicing constraints are frequent characteristics of real world TSPs.

Heuristic Extensions

Spanning forests have been used in the past for the partitioning and depot location portion of multiple depot TSPs (23). This research shows that the technique is useful when a large number of potential depot combinations exist. The research also shows that MSFs are somewhat limited in their ability to accurately prioritize the inclusion (or exclusion) of depots when there are many candidates from which to choose. Fortunately for this specific application (the DCS network), the limitation is, in some measure, ameliorated by manually altering the depot closure sequence. From a practical standpoint, this computationally "un-pure" aspect must be balanced with the fact that a truly exceptional depot location heuristic still evades the state-of-the-art in this field. The research shows that the MSF, though not without disadvantage, is a useful tool for this application.

The Clarke-Wright extensions developed in Chapter III are a key part of the heuristic used for the DCS network, and no significant drawbacks are noticeable in their implementation. The code used in this research incorporates the multiple-servicing extension proposed by Beltrami and Bodin (4:417). More importantly, this study develops a range constrained version of the Clarke-Wright algorithm. This inclusion of range limitation is critical to the DCS formulation. When run with the MSF output, the CW heuristic may be used in multiple depot applications, which broadens its scope from the single-depot TSP application for which it was originally developed.

Follow-on Research

Follow-on research topics fall into two broad categories: 1) recommended study by DCS prior to effecting any solution proposed in this document; and 2) supplementary analysis which would augment the body of knowledge surrounding the extended multiple-depot, multiple TSP. There are numerous opportunities for inquiry in each category.

As became apparent in the course of the research, depot costs are not readily modelled. Prior to any alteration of depot locations, closure or construction costs must be thoroughly examined on a case by case basis. Inclusion of a penalty factor for depot construction is one modelling alternative which should be explored in further

research. Another important additional cost factor which was not previously addressed is the overland aspect of the DCS network. Clearly, a depot which is a significant trucking hub is not as good a candidate for closure as a depot whose sole mission is aerial transshipment, since the trucking support would also be displaced. Additionally, growth of a hub beyond a certain point may force negative economies of scale, since limitations on physical space or contractor fleet size may exist. Rethinking service requirements is also warranted whenever a major structural change is made to the network. What was formerly a convenient stop to make weekly may require a special trip after restructuring. Finally, the proposed routes all limit the crew day to 13 hours without overnight requirements (which even the current structure violates occasionally). However, the routes tend to average close to 13 hours, which is longer than the current average. Convincing a contractor to fly a few extended missions may prove easier than providing him a ceaseless string of long sorties. These are all issues which mathematical algorithms alone cannot resolve.

The larger issue of extended multiple-depot, multiple-tour TSP solution methodology is also replete with unanswered questions. This research provides empirical evidence of the upper error bound of the MSF/CW algorithm, but offers no theoretical one. Since both the spanning forest (as it relates to the TSP) and the Clarke-Wright

algorithm have been around for some time, their respective accuracies have no doubt been largely fathomed. However, the error incurred by a synthesis of the two methods remains unexplored. Since much of the error appears to be in the MSF portion of the duo, further exploration of methods which provide depot location and partitioning are warranted. One possible area for study is the use of statistical cluster analysis of demand locations to provide a location/partitioning heuristic. The multiple depot methods proposed by Golden also show some promise for application, though modifications for problem size would have to be addressed (12:113-148). Many other possibilities no doubt exist.

Summary

Reduction of overall network costs are achievable by altering the location of depots, depot assignments, and routes flown by the DCS contractors. This report shows that tailoring existing mathematical models to assist in this process is extremely beneficial. The tools offered in the research are adaptable to both near-term and long-term network strategies, and can be altered to resolve countless "what if" inquiries. Hopefully, their use will prove beneficial to both the Defense Courier Service and the Military Airlift Command.

Appendix A: Regression of Depot Costs

OBS	MSNS	STA	MILES	COST
1	8.0	46	155397	486
2	4.0	30	114920	523
3	4.0	23	96104	577
4	4.0	22	80132	811
5	4.0	21	85406	529
6	5.0	25	130798	602
7	4.2	15	165210	350
8	2.0	7	37924	287
9	1.8	10	41742	405

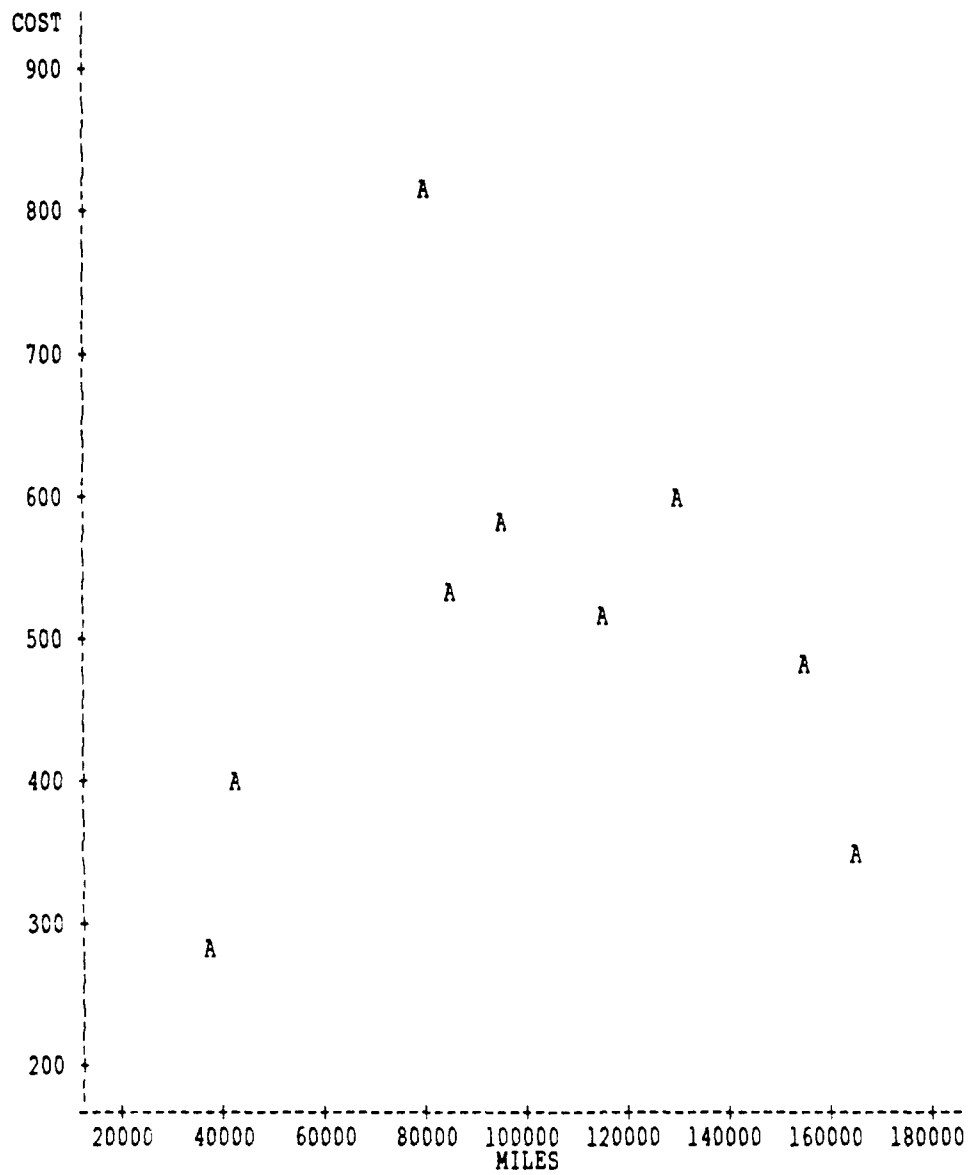
Correlation Analysis 4 'VAR' Variables: MSNS STA MILES COST

Variable	N	Simple Statistics		Sum	Minimum	Maximum
		Mean	Std Dev			
MSNS	9	4.1111	1.7947	37.0000	1.8000	8.0000
STA	9	22.1111	11.5590	199.0000	7.0000	46.0000
MILES	9	100848	45216	907633	37924	165210
COST	9	507.7778	154.5031	4570	287.0000	811.0000

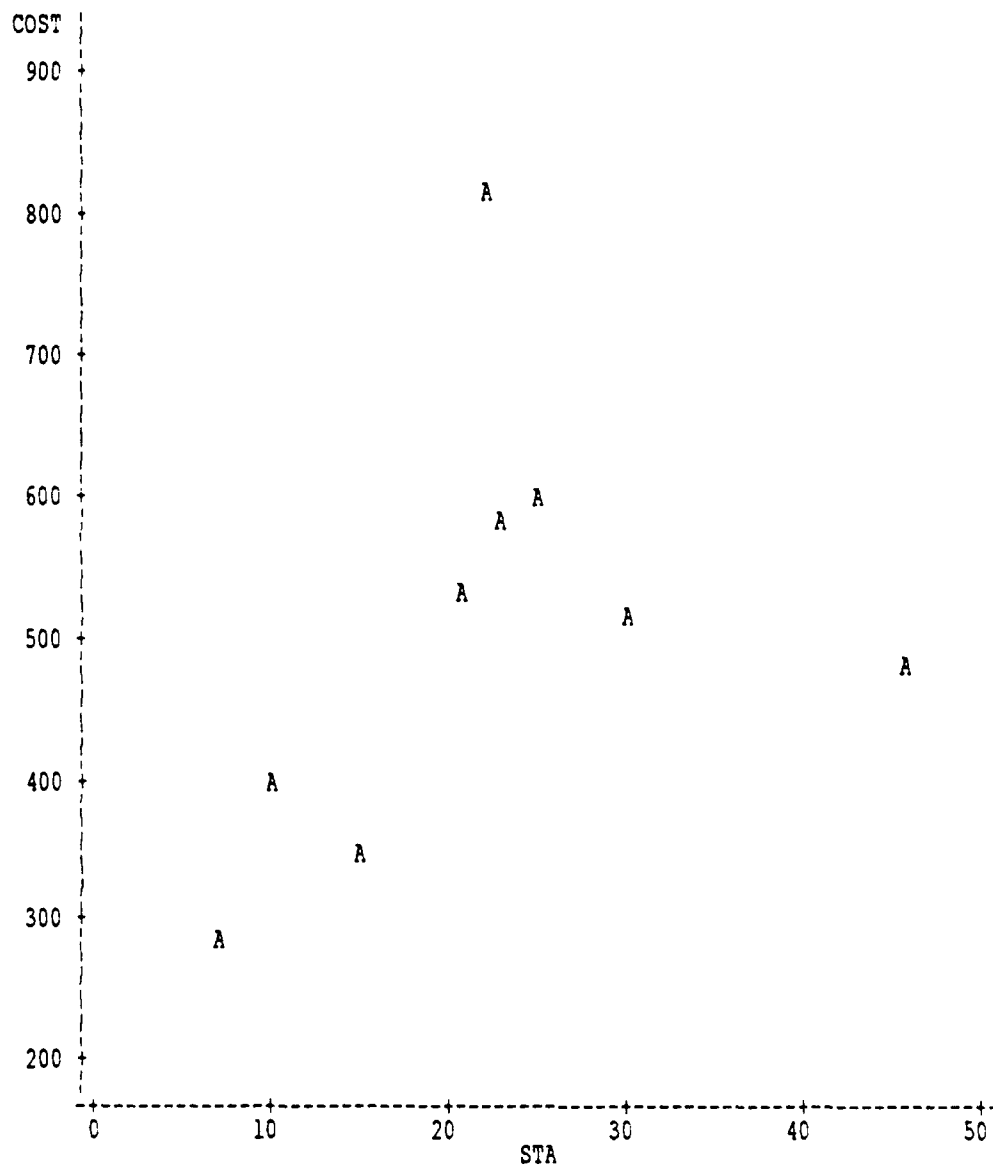
Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 9

	MSNS	STA	MILES	COST
MSNS	1.00000 0.0	0.92724 0.0003	0.79619 0.0102	0.28996 0.4491
STA	0.92724 0.0003	1.00000 0.0	0.65169 0.0572	0.39050 0.2988
MILES	0.79619 0.0102	0.65169 0.0572	1.00000 0.0	0.08450 0.8289
COST	0.28996 0.4491	0.39050 0.2988	0.08450 0.8289	1.00000 0.0

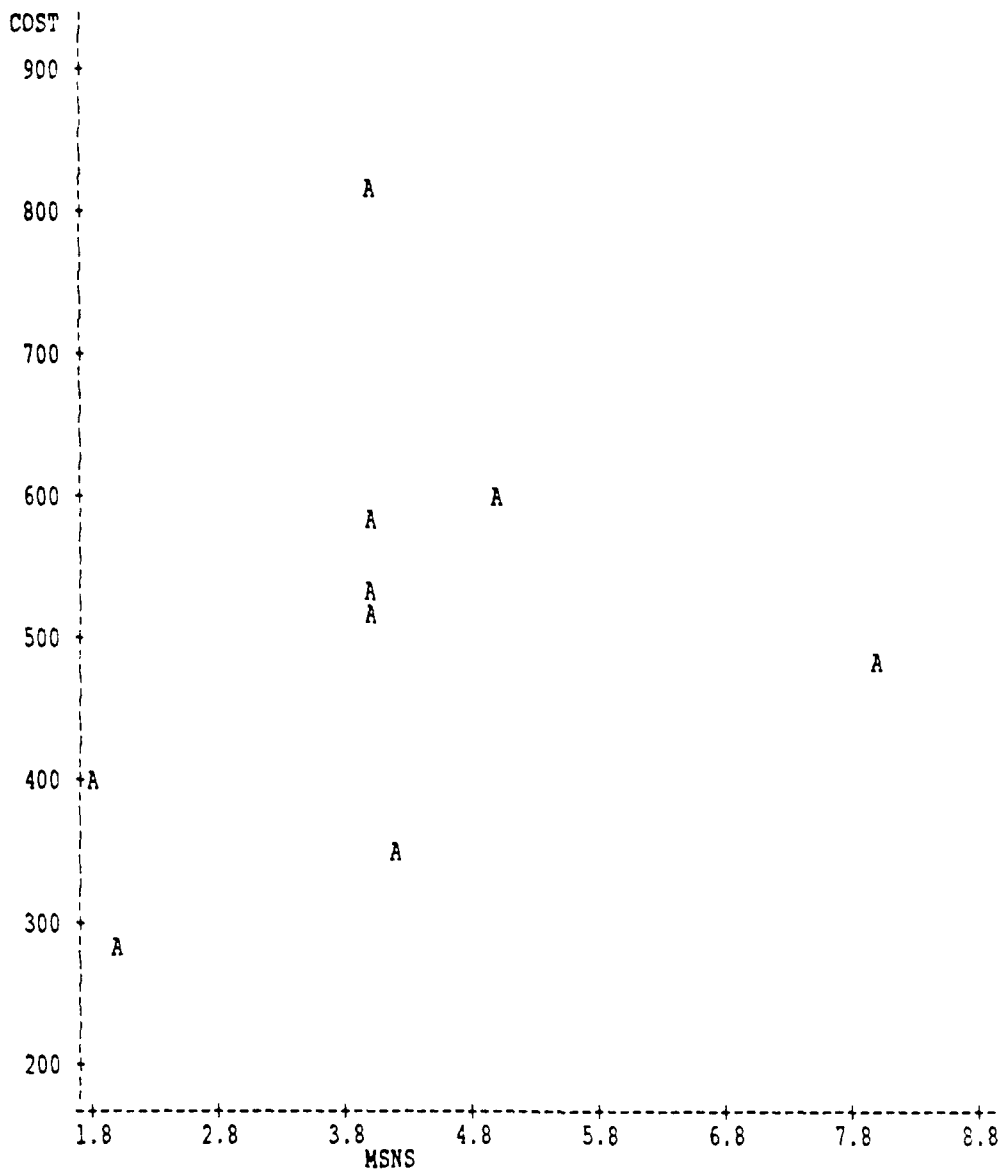
Plot of COST*MILES. Legend: A = 1 obs, B = 2 obs, etc.



Plot of COST*STA. Legend: A = 1 obs, B = 2 obs, etc.



Plot of COST*MSNS. Legend: A = 1 obs, B = 2 obs, etc.



Model: MODEL1
Dependent Variable: COST

		Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	1	1363.61815	1363.61815	0.050	0.8289	
Error	7	189605.93741	27086.56249			
C Total	8	190969.55556				
Root MSE		164.57996	R-square	0.0071		
Dep Mean		507.77778	Adj R-sq	-0.1347		
C.V.		32.41181				
Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	
INTERCEP	1	478.658966	140.89780276	3.397	0.0115	
MILES	1	0.000289	0.00128688	0.224	0.8289	

Model: MODEL2
Dependent Variable: COST

Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	1	16055.59436	16055.59436	0.643	0.4491	
Error	7	174913.96119	24987.70874			
C Total	8	190969.55556				
Root MSE		158.07501	R-square	0.0841		
Dep Mean		507.77778	Adj R-sq	-0.0468		
C.V.		31.13075				
Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	
INTERCEP	1	405.159538	138.43875239	2.927	0.0221	
MSNS	1	24.961194	31.13976789	0.802	0.4491	

Model: MODEL 3
Dependent Variable: COST

Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	1	29121.56813	29121.56813	1.260	0.2988	
Error	7	161847.98742	23121.14106			
C Total	8	190969.55556				
Root MSE		152.05637	R-square	0.1525		
Dep Mean		507.77778	Adj R-sq	0.0314		
C.V.		29.94546				
Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	
INTERCEP	1	392.365593	114.64920757	3.422	0.0111	
STA	1	5.219647	4.65091444	1.122	0.2988	

Model: MODEL4
Dependent Variable: COST

Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	2	27230.05559	13615.02779	0.499	0.6303	
Error	6	163739.49997	27289.91666			
C Total	8	190969.55556				
Root MSE		165.19660	R-square	0.1426		
Dep Mean		507.77778	Adj R-sq	-0.1432		
C.V.		32.53325				
Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	
INTERCEP	1	430.272902	149.90425236	2.870	0.0284	
MSNS	1	52.364068	53.78561961	0.974	0.3679	
MILES	1	-0.001366	0.00213488	-0.640	0.5459	

Model: MODEL 5
Dependent Variable: COST

Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	2	38713.50936	19356.75468	0.763	0.5068	
Error	6	152256.04620	25376.00770			
C Total	8	190969.55556				
Root MSE		159.29849	R-square	0.2027		
Dep Mean		507.77778	Adj R-sq	-0.0630		
C.V.		31.37169				
Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	
INTERCEP	1	437.275143	140.57764382	3.111	0.0208	
MILES	1	-0.001010	0.00164220	-0.615	0.5613	
STA	1	7.793507	6.42391661	1.213	0.2706	

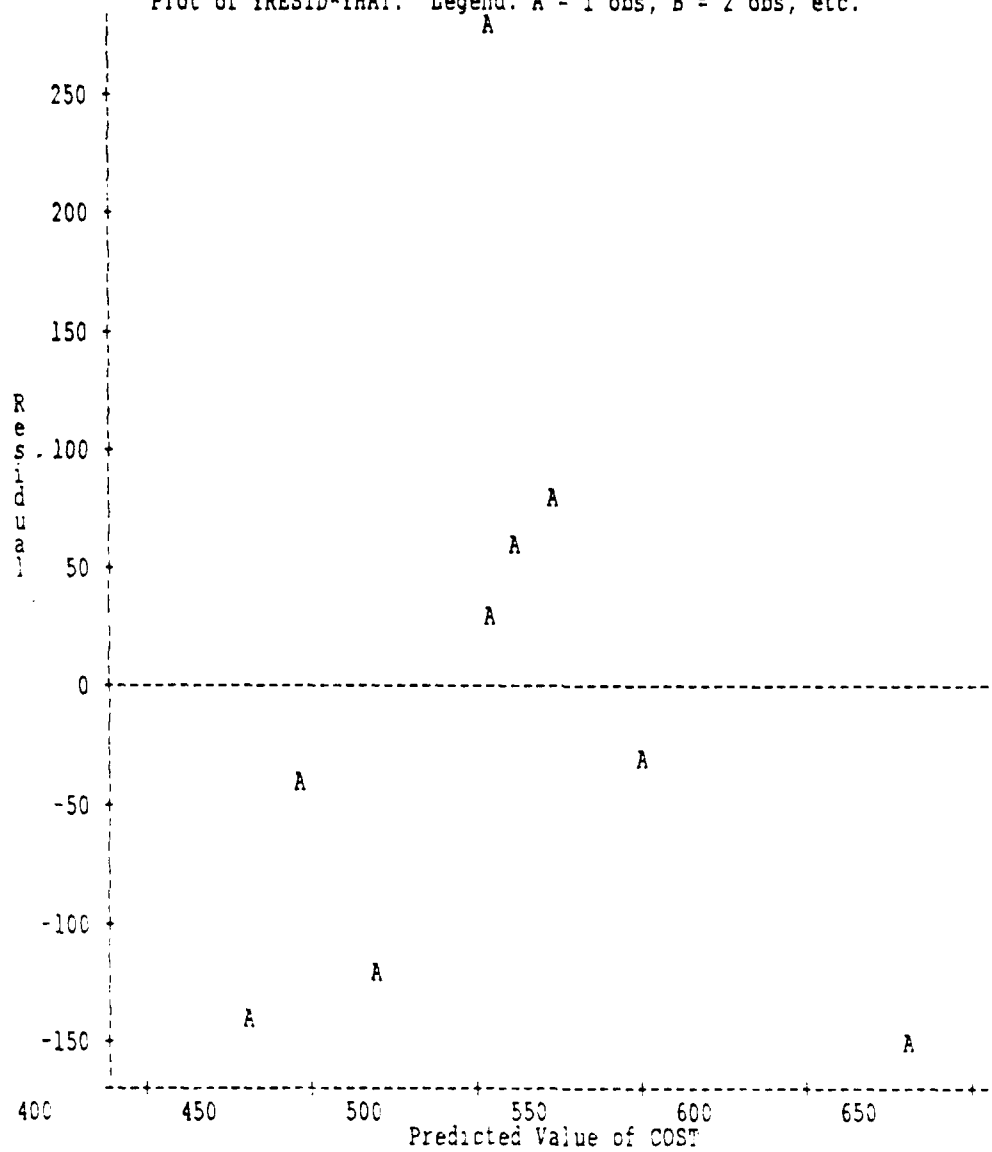
Model: MODEL6

Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	2	36208.44250	18104.22125	0.702	0.5322	
Error	6	154761.11305	25793.51884			
C Total	8	190969.55556				
Root MSE		160.60361	R-square	0.1896		
Dep Mean		507.77778	Adj R-sq	-0.0805		
C.V.		31.62872				
Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	
INTERCEP	1	433.452592	144.24939131	3.005	0.0239	
MSNS	1	-44.286491	84.48881151	-0.524	0.6190	
STA	1	11.595612	13.11839689	0.884	0.4108	

Model: FULL MODEL
Dependent Variable: COST

Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	3	39310.16210	13103.38737	0.432	0.7394	
Error	5	151659.39346	30331.87869			
C Total	8	190969.55556				
Root MSE		174.16050	R-square	0.2058		
Dep Mean		507.77778	Adj R-sq	-0.2706		
C.V.		34.29857				
Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	
INTERCEP	1	443.180599	159.35638901	2.781	0.0389	
MSNS	1	-17.431414	124.28578418	-0.140	0.8939	
STA	1	9.714722	15.39375717	0.631	0.5557	
MILES	1	-0.000779	0.00243552	-0.320	0.7621	

Plot of YRESID*YHAT. Legend: A = 1 obs, B = 2 obs, etc.



WILK-SHAPIRO
OBS SAMPsize NORMTSPV
1 9 0.93381

Appendix B: Spanning Forest and
Clarke-Wright Code

MSF:

C CAPT. S.F. BAKER
C MINIMAL SPANNING FOREST PROGRAM
C FOR DCS PROBLEM SET
C
C VARIABLE EXPLANATION:
C N: # OF NODES
C NDEP: # OF DEPOTS TO BE SELECTED
C (NOT INCLUDING FIXED DEPOTS)
C NFXDEP: # OF FIXED DEPOTS
C NDPCAN: # OF DEPOT CANDIDATES
C (NOT INCLUDING FIXED)
C NMND: N-NTDEP, OR NODES
C MINUS TOTAL DEPOTS
C NTDEP: TOTAL DEPOTS (NDEP+NFXDEP)
C LAT, LONG: COORDINATES OF NODE
C LATR, LONGR: COORDINATES IN RADIANS
C W: DISTANCE MATRIX
C FREQ: FREQUENCY OF DEMAND
C D1-D9: LOOP INDEX OF SELECTED DEPOTS
C NEAR: SELECTED NODE WHICH IS CLOSEST
C TO INDEXED NODE
C DIST: DISTANCE BETWEEN NEAR AND ITS INDEX
C TCOUNT: COUNTER OF SELECTED EDGES
C V: DUMMY VAR TO HOLD A CANDIDATE NODE
C DEPOT: DEPOT ASSOCIATED WITH A BRANCH
C TEDGE1: EMINENT NODE OF AN EDGE
C TEDGE2: INCIDENT NODE OF AN EDGE
C TWGT: SUMMED WEIGHTS OF A FOREST
C TW: DISTANCE FROM DEPOT TO NODE *
C SERVICING FREQUENCY
C BESTW: BEST TWGT OF DEPOT ITERATIONS
C EBST1, EBST2: BEST OF TEDGE1, TEDGE2
C ID, INF: DUMMY VARS TO HOLD MIN EDGES
C
* WHEN ALTERING PROBLEMS, THE FOLLOWING
* MUST BE CHANGED TO ACCOMODATE:
* SUCH CHANGES ARE FLAGGED BY AN ASTERIK
* IN A NEARBY COMMENT LINE
C 1) PARAMETER LINE AT TOP OF PROGRAM
C INSURE: NMND=N-NTDEP, NTDEP=NFXDEP+NDPCAN
C 2) LOOP 30, WHICH MUST REFLECT ALL POSSIBLE
C COMBINATIONS OF POTENTIAL DEPOTS. THERE
C WILL BE NDEP DO STATEMENTS.
C 3) THE DATA FILE MUST INCLUDE THE FIXED DEPOTS
C FIRST, FOLLOWED BY THE CANDIDATE DEPOTS,
C FOLLOWED BY THE REMAINING DEMANDS
C 4) THE OPEN STATEMENTS IN DECLARATION SEGMENT
C MUST REFLECT DESIRED INPUT AND OUTPUT FILENAMES

```

C
C DECLARATIONS
*
    PARAMETER(N=181,NDEP=8,NFXDEP=3,
1  NDPCAN=27,NMND=170,NTDEP=11)
    REAL LAT(N),LONG(N)
    DOUBLE PRECISION LATR(N),LONGR(N)
    INTEGER W(N,N),FREQ(N),D(NTDEP),D1,D2,
1  NEAR(N),DIST(N),TCOUNT,V,
2  TEDGE1(NMND),TEDGE2(NMND),TWGT,TW(N),
3  BESTW,EBST1(NMND),EBST2(NMND),ID,
4  D3,D4,D5,D6,D7,D8,D9,IDEP(NTDEP),DEPOT(N)
*
    OPEN(4,FILE='CON22.DAT',STATUS='OLD')
    OPEN(6,FILE='CON8A.OUT',STATUS='NEW')
    INF=3000
    BESTW=5000000
C
C INPUT LOCATIONS
C
    DO 5 I=1,N
        READ(4,100) LAT(I),LONG(I),FREQ(I)
*
* INPUT ECHO IF DESIRED
*     WRITE(6,100) LAT(I),LONG(I),FREQ(I)
C
C CONVERT TO RADIANS
C
    LATR(I)=((LAT(I)-AINT(LAT(I)))/.6
1      +AINT(LAT(I)))*3.141592653/180
    LONGR(I)=((LONG(I)-AINT(LONG(I)))/.6
1      +AINT(LONG(I)))*3.141592653/180
5    CONTINUE
C
C COMPUTE DISTANCE MATRIX
C
    DO 10 I=1,N
        DO 10 J=1,I
            IF (I.EQ.J) THEN
                W(I,J)=0
            ELSE
                W(I,J)=INT(3956.013*ACOS(SIN(LATR(I))
1      *SIN(LATR(J))+COS(LATR(I))*COS(LATR(J))
2      *COS(ABS(LONGR(J)-LONGR(I)))))+150
                W(J,I)=W(I,J)
            ENDIF
10    CONTINUE
C
    DO 20 I=1,N
        WRITE(6,200) (W(I,J),J=1,N)
20    CONTINUE
C
C DEFINE FIXED DEPOTS
C

```

```

        DO 21 I=1,NFXDEP
          D(I)=I
21      CONTINUE
C
C LOOP FOR DEPOT CHOICE ITERATIONS
C
*
        DO 30 D1=NFXDEP+1,NFXDEP+NDPCAN-NDEP+1
          D(NFXDEP+1)=D1
        DO 30 D2=D1+1,NFXDEP+NDPCAN-NDEP+2
          D(NFXDEP+2)=D2
        DO 30 D3=D2+1,NFXDEP+NDPCAN-NDEP+3
          D(NFXDEP+3)=D3
        DO 30 D4=D3+1,NFXDEP+NDPCAN-NDEP+4
          D(NFXDEP+4)=D4
        DO 30 D5=D4+1,NFXDEP+NDPCAN-NDEP+5
          D(NFXDEP+5)=D5
        DO 30 D6=D5+1,NFXDEP+NDPCAN-NDEP+6
          D(NFXDEP+6)=D6
        DO 30 D7=D6+1,NFXDEP+NDPCAN-NDEP+7
          D(NFXDEP+7)=D7
        DO 30 D8=D7+1,NFXDEP+NDPCAN-NDEP+8
          D(NFXDEP+8)=D8
C
C RESET COUNTERS BETWEEN ITERATIONS
C INDENTS RESTARTED IN CODE
C
        ID=3000
        V=0
        TCOUNT=0
        TWGT=0
        DO 35 J=1,N
          TW(J)=0
35      CONTINUE
C
C SET NEAR EQUAL TO NEAREST DEPOT
C
        DO 40 J=1,N
          ID=3000
          DO 40 I=1,NFXDEP+NDEP
            IF (W(D(I),J).LT.ID) THEN
              NEAR(J)=D(I)
              DEPOT(J)=NEAR(J)
              DIST(J)=W(D(I),J)
              ID=W(D(I),J)
            ENDIF
          CONTINUE
40      CONTINUE
C
C SET DEPOTS NEAR NOTHING IMPLYING
C CURRENT INCLUSION INTO FOREST
C
        DO 45 I=1,NFXDEP+NDEP

```

```

        NEAR(D(I))=0
        DEPOT(D(I))=D(I)
45    CONTINUE
C
C SELECT MINIMUM EDGE
C
50    IF (TCOUNT.LT.NMND) THEN
        MIN=INF
        DO 60 J=1,N
C CHECK FOR QUALIFIED EDGE
            IF ((NEAR(J).GT.0).AND.
1          (DIST(J).LT.MIN).AND.
2          (W(DEPOT(NEAR(J)),J).LT.1000)) THEN
C IF BEST AND QUALIFIED, SELECT
                V=J
                MIN=DIST(J)
            ENDIF
60    CONTINUE
C
C PENALTY FOR INFEASIBILITY
C
        IF (MIN.EQ.INF) DIST(V)=1000000
C
C UPDATE FOREST WITH NEW BRANCH
C
        TCOUNT=TCOUNT+1
        TEDGE1(TCOUNT)=NEAR(V)
        TEDGE2(TCOUNT)=V
        TW(V)=TW(NEAR(V))+DIST(V)
        TWGT=TWGT+TW(V)*FREQ(V)
        DEPOT(V)=DEPOT(NEAR(V))
        NEAR(V)=0
C
C UPDATE NEAR
C
        DO 70 J=1,N
            IF (NEAR(J).NE.0) THEN
                IF (W(J,NEAR(J)).GT.W(J,V)
1          .AND.(W(DEPOT(V),J).LT.1000)) THEN
                    DIST(J)=W(J,V)
                    NEAR(J)=V
                ENDIF
            ENDIF
70    CONTINUE
        GO TO 50
    ENDIF
C
C STORE FOREST AS BEST IF APPLICABLE
C
        IF (TWGT.LT.BESTW) THEN
            BESTW=TWGT
            DO 80 J=1,NMND
                EBST1(J)=TEDGE1(J)

```

```

      EBST2(J)=TEDGE2(J)
80    CONTINUE
      DO 81 J=1,NTDEP
        IDEP(J)=D(J)
81    CONTINUE
      ENDIF
30    CONTINUE
C
C WRITE RESULTS
C
      WRITE(6,*)'BEST WEIGHT=',BESTW
      WRITE(6,*)'DEPOTS='
      WRITE(6,200) (IDEP(I), I=1,NTDEP)
      WRITE(6,*)'EMINATING NODES ON TOP'
      WRITE(6,*) 'INCIDENT NODES BELOW'
      JU=NMND
      JL=1
90    IF (JU.LE.10) THEN
      WRITE(6,300) (EBST1(J), J=JL,NMND)
      WRITE(6,300) (EBST2(J), J=JL,NMND)
      WRITE(6,*)
      STOP
    ELSE
      WRITE(6,300) (EBST1(J), J=JL,JL+9)
      WRITE(6,300) (EBST2(J), J=JL,JL+9)
      WRITE(6,*)
    ENDIF
      JU=JU-10
      JL=JL+10
      GO TO 90
100   FORMAT(1X,F5.2,3X,F6.2,2X,I2)
200   FORMAT(1X,11I5)
300   FORMAT(1X,10I5)
      END

```


CLARKE-WRIGHT CODE:

```

C CAPT S.F. BAKER
C MODIFIED CLARKE-WRIGHT ALGORITHM
C WRIGHT-PATT NEAR TERM DEPOT MODEL
C
C VARIABLE EXPLANATION:
C N: NUMBER OF DEMAND POINTS (NODES OTHER
C   THAN DEPOT WITH
C   FREQUENCY 2 COUNTS AS 2)
C LAT, LONG: LATITUDE AND LONGITUDE OF NODE
C LATR, LONGR: LAT AND LONG IN RADIANS
C DEP: NUMBER OF EDGES A NODE SHARES WITH DEPOT
C C: DEMAND FREQUENCY OF A NODE
C W: DISTANCE BETWEEN 2 NODES
C S: POTENTIAL SAVINGS FROM ROUTE CONSOLIDATION
C NCV: NODES INCLUDED (J) IN SAME TOUR AS I
C R: DISTANCE FROM ORIGIN OF A NODE IF 1
C   ORIGIN EDGE IS SEVERED
C NC: TOUR ASSOCIATED WITH NODE I
C U,V: DUMMY VARS HOLDING CURRENT
C   CONSOLIDATION OPTION
C CI, IRIJ, ICV: DUMMY VARS HOLDING CURRENT
C   C,R,NC
C MIN: BEST KNOWN SAVINGS IN ITERATION
C TOT: MILAGE TOTAL
C
* REQUIREMENTS FOR ALTERING DATA SET
C 1) CHANGE PARAMETER TO REFLECT
C   TOTAL DEMANDS (DEPOT COUNTS AS
C   1 ALWAYS!!!, OTHER NODES COUNT AS THEIR
C   DEMAND FREQUENCY
C 2) INSURE DEPOT IS FIRST IN DATA SET
C   AND HAS FREQUENCY 1 REGARDLESS OF
C   ACTUAL FREQUENCY
C 3) INSURE OPEN STATEMENTS REFLECT DESIRED
C   INPUT AND OUTPUT FILES
C
C DECLARATIONS
C
*
      PARAMETER(N=20)
      REAL LAT(N), LONG(N)
      DOUBLE PRECISION LATR(N), LONGR(N)
      INTEGER DEP(N), C(N), W(N,N), S(N,N),
1 NCV(N,N), R(N), U,V, CI, NC(N), TOT
*
      OPEN(4, FILE='PFF.DAT', STATUS='OLD')
      OPEN(6, FILE='PFF.OUT', STATUS='NEW')
C
C OUTPUT SETUP
C AND INPUT LOCATIONS
C

```

```

      I=1
2      IF (I.LE.N) THEN
          READ(4,100) LAT(I),LONG(I),C(I)
          CI=C(I)
C      DUPLICATE NODES IF NECESSARY TO REFLECT DEMAND
          IF (I.GT.1) THEN
              DO 5 J=0,CI-1
                  LAT(I+J)=LAT(I)
                  LONG(I+J)=LONG(I)
                  C(I+J)=C(I)
*
*      INPUT ECHO IF DESIRED
*
*          WRITE(6,100) LAT(I+J),LONG(I+J),C(I+J)
*
C      LOAD INITIAL TOUR NUMBERS, TOUR LOADS
          DO 5 K=0,CI-1
              NC(I+J)=I+J
              NCV(NC(I+J),I+K)=1
5          CONTINUE
          ELSE
              CONTINUE
          ENDIF
C      INCREMENT I TO NEXT NODE
          I=I+CI
          GOTO 2
          ELSE
              CONTINUE
          ENDIF
C      CONVERT TO RADIANS
          DO 8 I=1,N
              LATR(I)=((LAT(I)-AINT(LAT(I)))/.6
1              +AINT(LAT(I)))*3.141592653/180
              LONGR(I)=((LONG(I)-AINT(LONG(I)))/.6
1              +AINT(LONG(I)))*3.141592653/180
8          CONTINUE
C
C      INITIALIZE ARRAYS AND
C      COMPUTE DISTANCE MATRIX
C
          DO 10 I=1,N
              DEP(I)=2
C      SET DISTANCE TO 0 IF IDENTICAL LOCATION
          DO 10 J=1,I
              DIFLAT=ABS(LAT(I)-LAT(J))
              DIFLON=ABS(LONG(I)-LONG(J))
              IF ((DIFLAT.LT..01).OR.(DIFLON.LT..01)) THEN
                  W(I,J)=0
              ELSE
                  W(I,J)=INT(3956.013*ACOS(SIN(LATR(I))
1                  *SIN(LATR(J))+COS(LATR(I))*COS(LATR(J))
2                  *COS(ABS(LONGR(J)-LONGR(I)))))+150
C      INITIAL R AND SAVINGS CALCULATION

```

```

        R(I)=W(I,1)
        S(I,J)=W(I,1)+W(J,1)-W(I,J)
    ENDIF
10    CONTINUE
*
* OUTPUT DISTANCE HALF MATRIX
* IF IT IS SMALL ENOUGH FOR
* DESIRED OUTPUT
*
* DO 20 I= 1,N
* COMMENT OUT IF N IS LARGE
* WRITE(6,200) (W(I,J),J=1,I)
*20    CONTINUE
*
        WRITE(6,*)'ARCS IN THE SOLUTION'
C
C FIND GREATEST SAVINGS
C DISQUALIFY IF
C 1) NODE IS INTERNAL TO A ROUTE
C 2) SAVINGS NOT THE BEST
C 3) RANGE EXCEEDED
C 4) TOUR INCLUDES > 1 VISITS/CLUSTER
C
40    DO 50 I=2,N
        DO 50 J=1,I-1
            IF ((DEP(I).LE.0).OR.(DEP(J).LE.0)) GOTO 70
            IF (S(I,J).LE.MIN) GOTO 70
            IRIJ=R(I)+R(J)+W(I,J)
            IF (IRIJ.GT.2600) GOTO 70
            DO 60 K=1,N
                NCVI=NCV(NC(I),K)+NCV(NC(J),K)
                IF (NCVI.GT.1) GOTO 70
60        CONTINUE
C
C HOLD BEST SAVINGS IN PASS
C
        MIN =S(I,J)
        U=I
        V=J
70    CONTINUE
C
C UPDATE ARRAYS AND WRITE NEW ARC
C
50    CONTINUE
C QUIT IF NO QUALIFIED CONSOLIDATION
    IF(MIN.EQ.0) GOTO 80
C UPDATE CONSOLIDATED NODE ARRAYS
    DEP(U)=DEP(U)-1
    DEP(V)=DEP(V)-1
C UPDATE RANGE VARS
    IRU=R(U)
    IRV=R(V)
    DO 55 J=1,N

```

```

        IF (NC(J).EQ.NC(U))
1      R(J)=R(J)+W(U,V)+IRV-W(U,1)
        IF (NC(J).EQ.NC(V))
1      R(J)=R(J)+W(U,V)+IRU-W(V,1)
55    CONTINUE
        S(U,V)=0
        ICV=NC(V)
        DO 65 J=1,N
            NCV(NC(U),J)=NCV(NC(U),J)+NCV(NC(V),J)
65    CONTINUE
C CONSOLIDATE TOUR LOADING ARRAYS INTO ONE TOUR
        DO 68 J=1,N
            IF (NC(J).EQ.ICV) NC(J)=NC(U)
68    CONTINUE
C ADD NEW LEG TO TOTAL
        TOT=TOT+W(U,V)
C WRITE NEW LINK AND RETURN
        WRITE(6,300) U,V
        MIN=0
        GOTO 40
80    CONTINUE
C
C WRITE REMAINING DEPOT CONNECTIONS
C
        DO 90 I=2,N
            IF(DEP(I).EQ.1) THEN
                TOT=TOT+W(I,1)
                WRITE(6,500) I
            ELSEIF (DEP(I).EQ.2) THEN
                TOT=TOT+2*W(I,1)
                WRITE(6,600) I
            ELSE
                CONTINUE
            ENDIF
90    CONTINUE
C WRITE TOTAL COST
        WRITE(6,*) 'THE TOTAL COST='
        WRITE(6,400) TOT
100   FORMAT(1X,F5.2,3X,F6.2,2X,I2)
200   FORMAT(1X,I5I4)
300   FORMAT(1X,I3)
400   FORMAT(1X,I6)
500   FORMAT(1X,I3,' 1')
600   FORMAT(1X,I3,' 1 TWICE')
END

```

Appendix C: Validation Code and Output

The code below is used to solve the region 1 validation with optimal depots. It is typical of the code used for the other regions.

```
* CAPT S.F. BAKER
* DCS MULTIPLE DEPOT OPTIMIZATION REGION 1
*
* POTENTIAL DEPOTS AT MCCHORD, TRAVIS AFB
* DEMANDS AT MCCHORD, TRAVIS, BOISE, KLAMATH FALLS,
* AND 2 DEMANDS AT MT HOME
* ALL VARS 0,1 EXCEPT #ACFT (M1,M2), WHICH ARE INT,
* AND D3 - D7, WHICH ARE UNRESTRICTED
* OBJECTIVE COEFFICIENTS ARE GREAT CIRCLE STATUTE
* MILES PLUS 150 (GROUND TIME), EXCEPT FOR DEPOT
* COEFFICIENTS, WHICH ARE COSTS CONVERTED TO MILES
* X VARS ARE EDGES, YVARS ARE DEPOT LOCATION BINARY,
* M VARS ARE # ACFT AT A STATION
* SUBSCRIPTS: 1,5=KTCM; 2,6=KSUU; 3=KLMT; 4=KBOI;
* 7,8=KMUO
..TITLE
REG11
*
..OBJECTIVE MINIMIZE
*
[[ 764 X12 + 496 X13 + 541 X14 + 0 X15 + 764 X16
+ 578 X17 + 578 X18
+ 419 X23 + 621 X24 + 764 X25 + 0 X26
+ 608 X27 + 608 X28
+ 445 X34 + 496 X35 + 419 X36 + 454 X37 + 454 X38
+ 541 X45 + 621 X46 + 190 X47 + 190 X48
+ 764 X56 + 578 X57 + 578 X58
+ 608 X67 + 608 X68
+ 764 X21 + 496 X31 + 541 X41 + 0 X51 + 764 X61
+ 578 X71 + 578 X81
+ 419 X32 + 621 X42 + 764 X52 + 0 X62
+ 608 X72 + 608 X82
+ 445 X43 + 496 X53 + 419 X63 + 454 X73 + 454 X83
+ 541 X54 + 621 X64 + 190 X74 + 190 X84
+ 764 X65 + 578 X75 + 578 X85
+ 608 X76 + 608 X86
+ 3382 Y1 + 3382 Y2 ] + 0 M1 + 0 M2 ]
+ 0 D3 + 0 D4 + 0 D5 + 0 D6 + 0 D7
*
..CONSTRAINTS
*
* 1 VISIT PER DEMAND POINT
*
C1: X13 + X14 + X15 + X16 + X17 + X18 - M1 = 0
C2: X23 + X24 + X25 + X26 + X27 + X28 - M2 = 0
C3: X31 + X32 + X34 + X35 + X36 + X37 + X38 = 1
C4: X41 + X42 + X43 + X45 + X46 + X47 + X48 = 1
```

C5: $X51 + X52 + X53 + X54 + X56 + X57 + X58 = 1$
 C6: $X61 + X62 + X63 + X64 + X65 + X67 + X68 = 1$
 C6A: $X71 + X72 + X73 + X74 + X75 + X76 = 1$
 C6B: $X81 + X82 + X83 + X84 + X85 + X86 = 1$
 *
 C7: $X31 + X41 + X51 + X61 + X71 + X81 - M1 = 0$
 C8: $X32 + X42 + X52 + X62 + X72 + X82 - M2 = 0$
 C9: $X13 + X23 + X43 + X53 + X63 + X73 + X83 = 1$
 C10: $X14 + X24 + X34 + X54 + X64 + X74 + X84 = 1$
 C11: $X15 + X25 + X35 + X45 + X65 + X75 + X85 = 1$
 C12: $X16 + X26 + X36 + X46 + X56 + X76 + X86 = 1$
 C12A: $X17 + X27 + X37 + X47 + X57 + X67 = 1$
 C12B: $X18 + X28 + X38 + X48 + X58 + X68 = 1$
 *
 * SUBTOUR BREAKING WITH RANGE LIMITATION
 *
 C48: $2600 X43 + D4 - D3 \leq 2155$
 C49: $2600 X34 + D3 - D4 \leq 2155$
 C50: $2600 X53 + D5 - D3 \leq 2104$
 C51: $2600 X35 + D3 - D5 \leq 2104$
 C52: $2600 X63 + D6 - D3 \leq 2181$
 C53: $2600 X36 + D3 - D6 \leq 2181$
 CE3: $2600 X73 + D7 - D3 \leq 2146$
 CE4: $2600 X37 + D3 - D7 \leq 2146$
 CE5: $2600 X83 + D7 - D3 \leq 2146$
 CE6: $2600 X38 + D3 - D7 \leq 2146$
 C54: $2600 X54 + D5 - D4 \leq 2059$
 C55: $2600 X45 + D4 - D5 \leq 2059$
 C56: $2600 X64 + D6 - D4 \leq 1979$
 C57: $2600 X46 + D4 - D6 \leq 1979$
 CE8: $2600 X74 + D7 - D4 \leq 2410$
 CE9: $2600 X47 + D4 - D7 \leq 2410$
 CE1: $2600 X84 + D7 - D4 \leq 2410$
 CE2: $2600 X48 + D4 - D7 \leq 2410$
 C58: $2600 X65 + D6 - D5 \leq 1836$
 C59: $2600 X56 + D5 - D6 \leq 1836$
 C60: $2600 X75 + D7 - D5 \leq 2022$
 C61: $2600 X57 + D5 - D7 \leq 2022$
 C62: $2600 X85 + D7 - D5 \leq 2022$
 C63: $2600 X58 + D5 - D7 \leq 2022$
 C64: $2600 X76 + D7 - D6 \leq 2022$
 C65: $2600 X67 + D6 - D7 \leq 2022$
 C66: $2600 X86 + D7 - D6 \leq 2022$
 C67: $2600 X68 + D6 - D7 \leq 2022$
 *
 * RANGE COMPUTATION FROM DEPOT
 *
 C82: $496 X13 - D3 \leq 0$
 C83: $541 X14 - D4 \leq 0$
 C84: $764 X16 - D6 \leq 0$
 CG4: $578 X17 - D7 \leq 0$
 CG5: $578 X18 - D7 \leq 0$
 C86: $419 X23 - D3 \leq 0$

C87: 621 X24 - D4 <= 0
 C88: 764 X25 - D5 <= 0
 CG8: 608 X27 - D7 <= 0
 CG9: 608 X28 - D7 <= 0

*

* RANGE COMPUTATION TO DEPOT

*

C89: 496 X31 + D3 <= 2600
 C90: 541 X41 + D4 <= 2600
 C91: 764 X61 + D6 <= 2600
 CH1: 578 X71 + D7 <= 2600
 CH2: 578 X81 + D7 <= 2600
 C92: 419 X32 + D3 <= 2600
 C93: 621 X42 + D4 <= 2600
 C94: 764 X52 + D5 <= 2600
 CH4: 608 X72 + D7 <= 2600
 CH5: 608 X82 + D7 <= 2600

*

* CHAIN BARRING

*

C76: X13 + 3 X34 + X24 + X31 + 3 X43 + X42 <= 4
 C78: X13 + 3 X36 + X26 + X31 + 3 X63 + X62 <= 4
 C77: X13 + 3 X37 + X27 + X31 + 3 X73 + X72 <= 4
 CG7: X13 + 3 X38 + X28 + X31 + 3 X83 + X82 <= 4
 C79: X14 + 3 X34 + X23 + X41 + 3 X43 + X32 <= 4
 C13: X14 + 3 X46 + X26 + X41 + 3 X64 + X62 <= 4
 C80: X14 + 3 X47 + X27 + X41 + 3 X74 + X72 <= 4
 CH0: X14 + 3 X48 + X28 + X41 + 3 X84 + X82 <= 4
 C14: X15 + 3 X35 + X23 + X51 + 3 X53 + X32 <= 4
 C15: X15 + 3 X56 + X26 + X51 + 3 X65 + X62 <= 4
 CA5: X15 + 3 X57 + X27 + X51 + 3 X75 + X72 <= 4
 C16: X15 + 3 X58 + X28 + X51 + 3 X85 + X82 <= 4
 C16: X17 + 3 X73 + X23 + X71 + 3 X37 + X32 <= 4
 C16: X17 + 3 X74 + X24 + X71 + 3 X47 + X42 <= 4
 C16: X17 + 3 X76 + X26 + X71 + 3 X67 + X62 <= 4
 C16: X18 + 3 X38 + X23 + X81 + 3 X83 + X32 <= 4
 C16: X18 + 3 X48 + X24 + X81 + 3 X84 + X42 <= 4
 C16: X18 + 3 X68 + X26 + X81 + 3 X86 + X62 <= 4
 C17: X23 + 3 X24 + X14 + X32 + 3 X42 + X41 <= 4
 C18: X23 + 3 X35 + X15 + X32 + 3 X53 + X51 <= 4
 C19: X23 + 3 X37 + X17 + X32 + 3 X73 + X71 <= 4
 C19: X23 + 3 X38 + X18 + X32 + 3 X83 + X81 <= 4
 C20: X24 + 3 X34 + X13 + X42 + 3 X43 + X31 <= 4
 C21: X24 + 3 X45 + X15 + X42 + 3 X54 + X51 <= 4
 C22: X24 + 3 X47 + X17 + X42 + 3 X74 + X71 <= 4
 C22: X24 + 3 X48 + X18 + X42 + 3 X84 + X81 <= 4
 C23: X25 + 3 X35 + X13 + X52 + 3 X53 + X31 <= 4
 C24: X25 + 3 X45 + X14 + X52 + 3 X54 + X41 <= 4
 C25: X25 + 3 X57 + X17 + X52 + 3 X75 + X71 <= 4
 C25: X25 + 3 X58 + X18 + X52 + 3 X85 + X81 <= 4
 C26: X26 + 3 X36 + X13 + X62 + 3 X63 + X61 <= 4
 C27: X26 + 3 X46 + X14 + X62 + 3 X64 + X41 <= 4
 C28: X26 + 3 X56 + X15 + X62 + 3 X65 + X51 <= 4

+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

CC6: X15 + X51 + X72 + X27 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

CC7: X15 + X51 + X82 + X28 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

CC6: X17 + X71 + X32 + X23 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

C37: X17 + X71 + X42 + X24 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

CC6: X17 + X71 + X62 + X26 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

CC7: X17 + X71 + X82 + X28 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

CD6: X18 + X81 + X32 + X23 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

C37: X18 + X81 + X42 + X24 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

CC6: X18 + X81 + X62 + X26 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

CC7: X18 + X81 + X72 + X27 + 2 (X34 + X35 + X36 + X45
 + X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
 + X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
 + X75 + X85 + X76 + X86) <= 11

*

* ACFT ASSIGNED ONLY TO ACTIVE DEPOTS

*

C41: Y1 - M1 <= 0

C42: Y2 - M2 <= 0

C43: M1 - 10 Y1 <= 0

C44: M2 - 10 Y2 <= 0

*

* BOUNDS ON FLEET SIZE

*

C45: $M1 \leq 4$
C46: $M2 \leq 4$
C47: $Y1 + Y2 \geq 1$

Region 1 with optimal depot.

Laporte formulation output (of the input file on the previous pages):

Output explanation:

"REG11 "				
129, 63,	6792.0000			Since the MSF/CW output
"X12 "	0.0000,	764.0000		does not include depot
"X13 "	0.0000,	496.0000		cost, the objective
"X14 "	1.0000,	541.0000		function value for
"X15 "	0.0000,	0.0000		comparitive purposes
"X16 "	0.0000,	764.0000		is 6792-3382, or 3410.
"X17 "	1.0000,	578.0000		
"X18 "	0.0000,	578.0000		
"X23 "	0.0000,	419.0000		Node assignments:
"X24 "	0.0000,	621.0000		1,5 TCM
"X25 "	0.0000,	764.0000		2,6 SUU
"X26 "	0.0000,	0.0000		3 LMT
"X27 "	0.0000,	608.0000		4 BOI
"X28 "	0.0000,	608.0000		7,8 MUO
"X34 "	0.0000,	445.0000		
"X35 "	0.0000,	496.0000		Arc value is 1 if
"X36 "	0.0000,	419.0000		used.
"X37 "	0.0000,	454.0000		
"X38 "	0.0000,	454.0000		
"X45 "	0.0000,	541.0000		
"X46 "	0.0000,	621.0000		
"X47 "	0.0000,	190.0000		
"X48 "	1.0000,	190.0000		
"X56 "	0.0000,	764.0000		
"X57 "	0.0000,	578.0000		
"X58 "	0.0000,	578.0000		
"X67 "	0.0000,	608.0000		
"X68 "	0.0000,	608.0000		
"X21 "	0.0000,	764.0000		
"X31 "	1.0000,	496.0000		
"X41 "	0.0000,	541.0000		
"X51 "	1.0000,	0.0000		
"X61 "	0.0000,	764.0000		
"X71 "	0.0000,	578.0000		
"X81 "	0.0000,	578.0000		
"X32 "	0.0000,	419.0000		
"X42 "	0.0000,	621.0000		
"X52 "	0.0000,	764.0000		
"X62 "	0.0000,	0.0000		
"X72 "	0.0000,	608.0000		
"X82 "	0.0000,	608.0000		
"X43 "	0.0000,	445.0000		
"X53 "	0.0000,	496.0000		
"X63 "	1.0000,	419.0000		
"X73 "	0.0000,	454.0000		
"X83 "	0.0000,	454.0000		
"X54 "	0.0000,	541.0000		

"X64	",	0.0000,	621.0000	
"X74	",	0.0000,	190.0000	
"X84	",	0.0000,	190.0000	
"X65	",	0.0000,	764.0000	
"X75	",	0.0000,	578.0000	
"X85	",	1.0000,	578.0000	
"X76	",	1.0000,	608.0000	
"X86	",	0.0000,	608.0000	
"Y1	",	1.0000,	3382.0000	Depot is used if value
"Y2	",	0.0000,	3382.0000	is 1.
"M1	",	2.0000,	0.0000	Num of aircraft at a
"M2	",	0.0000,	0.0000	depot.
"D3	",	2104.0000,	0.0000	Odometer variable
"D4	",	541.0000,	0.0000	values.
"D5	",	1309.0000,	0.0000	
"D6	",	1685.0000,	0.0000	
"D7	",	731.0000,	0.0000	
"C1	",	0.0000,	0.0000	Constraint values and
"C2	",	0.0000,	0.0000	slack.
"C3	",	1.0000,	1.0000	
"C4	",	1.0000,	1.0000	
"C5	",	1.0000,	1.0000	
"C6	",	1.0000,	1.0000	
"C6A	",	1.0000,	1.0000	
"C6B	",	1.0000,	1.0000	
"C7	",	0.0000,	0.0000	
"C8	",	0.0000,	0.0000	
"C9	",	1.0000,	1.0000	
"C10	",	1.0000,	1.0000	
"C11	",	1.0000,	1.0000	
"C12	",	1.0000,	1.0000	
"C12A	",	1.0000,	1.0000	
"C12B	",	1.0000,	1.0000	
"C48	",	-1563.0000,	2155.0000	
"C49	",	1563.0000,	2155.0000	
"C50	",	-795.0000,	2104.0000	
"C51	",	795.0000,	2104.0000	
"C52	",	2181.0000,	2181.0000	
"C53	",	419.0000,	2181.0000	
"CE3	",	-1373.0000,	2146.0000	
"CE4	",	1373.0000,	2146.0000	
"CE5	",	-1373.0000,	2146.0000	
"CE6	",	1373.0000,	2146.0000	
"C54	",	768.0000,	2059.0000	
"C55	",	-768.0000,	2059.0000	
"C56	",	1144.0000,	1979.0000	
"C57	",	-1144.0000,	1979.0000	
"CE8	",	190.0000,	2410.0000	
"CE9	",	-190.0000,	2410.0000	
"CE1	",	190.0000,	2410.0000	
"CE2	",	2410.0000,	2410.0000	
"C58	",	376.0000,	1836.0000	
"C59	",	-376.0000,	1836.0000	

"C60	"	-578.0000,	2022.0000
"C61	"	578.0000,	2022.0000
"C62	"	2022.0000,	2022.0000
"C63	"	578.0000,	2022.0000
"C64	"	1646.0000,	2022.0000
"C65	"	954.0000,	2022.0000
"C66	"	-954.0000,	2022.0000
"C67	"	954.0000,	2022.0000
"C82	"	-2104.0000,	0.0000
"C83	"	-0.0000,	0.0000
"C84	"	-1685.0000,	0.0000
"CG4	"	-153.0000,	0.0000
"CG5	"	-731.0000,	0.0000
"C86	"	-2104.0000,	0.0000
"C87	"	-541.0000,	0.0000
"C88	"	-1309.0000,	0.0000
"CG8	"	-731.0000,	0.0000
"CG9	"	-731.0000,	0.0000
"C89	"	2600.0000,	2600.0000
"C90	"	541.0000,	2600.0000
"C91	"	1685.0000,	2600.0000
"CH1	"	731.0000,	2600.0000
"CH2	"	731.0000,	2600.0000
"C92	"	2104.0000,	2600.0000
"C93	"	541.0000,	2600.0000
"C94	"	1309.0000,	2600.0000
"CH4	"	731.0000,	2600.0000
"CH5	"	731.0000,	2600.0000
"C76	"	1.0000,	4.0000
"C78	"	2.0000,	4.0000
"C77	"	1.0000,	4.0000
"CG7	"	1.0000,	4.0000
"C79	"	1.0000,	4.0000
"C13	"	1.0000,	4.0000
"C80	"	1.0000,	4.0000
"CH0	"	2.0000,	4.0000
"C14	"	1.0000,	4.0000
"C15	"	1.0000,	4.0000
"CA5	"	1.0000,	4.0000
"C16	"	2.0000,	4.0000
"C16	"	1.0000,	4.0000
"C16	"	1.0000,	4.0000
"C16	"	2.0000,	4.0000
"C16	"	0.0000,	4.0000
"C16	"	1.0000,	4.0000
"C16	"	0.0000,	4.0000
"C17	"	1.0000,	4.0000
"C18	"	1.0000,	4.0000
"C19	"	1.0000,	4.0000
"C19	"	0.0000,	4.0000
"C20	"	1.0000,	4.0000
"C21	"	1.0000,	4.0000
"C22	"	1.0000,	4.0000

"C22	",	1.0000,	4.0000
"C23	",	1.0000,	4.0000
"C24	",	1.0000,	4.0000
"C25	",	1.0000,	4.0000
"C25	",	1.0000,	4.0000
"C26	",	1.0000,	4.0000
"C27	",	1.0000,	4.0000
"C28	",	1.0000,	4.0000
"C27	",	2.0000,	4.0000
"C28	",	0.0000,	4.0000
"C29	",	9.0000,	11.0000
"C30	",	9.0000,	11.0000
"C31	",	9.0000,	11.0000
"CC0	",	9.0000,	11.0000
"CC1	",	9.0000,	11.0000
"C32	",	9.0000,	11.0000
"C33	",	9.0000,	11.0000
"C34	",	9.0000,	11.0000
"CC3	",	9.0000,	11.0000
"CC4	",	9.0000,	11.0000
"C35	",	9.0000,	11.0000
"C36	",	9.0000,	11.0000
"C37	",	9.0000,	11.0000
"CC6	",	9.0000,	11.0000
"CC7	",	9.0000,	11.0000
"CC6	",	9.0000,	11.0000
"C37	",	9.0000,	11.0000
"CC6	",	9.0000,	11.0000
"CC7	",	9.0000,	11.0000
"CD6	",	8.0000,	11.0000
"C37	",	8.0000,	11.0000
"CC6	",	8.0000,	11.0000
"CC7	",	8.0000,	11.0000
"C41	",	-1.0000,	0.0000
"C42	",	0.0000,	0.0000
"C43	",	-8.0000,	0.0000
"C44	",	0.0000,	0.0000
"C45	",	2.0000,	4.0000
"C46	",	0.0000,	4.0000
"C47	",	1.0000,	1.0000

Region 1 with 1 depot.

MSF output:

```
47.08  122.28  1
38.15  121.55  1
42.09  121.44  1
43.33  116.13  1
43.02  115.52  2
  0
 763    0
495  419    0
541  621  445    0
578  607  454  189    0
BEST WEIGHT=          4303
EMANATING NODES ON TOP
INCIDENT NODES BELOW
    2    3    4    3
    3    4    5    1
```

Output Explanation:

```
1 TCM Lat/Long, service freq
2 SUU  "
3 LMT  "
4 BOI  "
5 MUO  "
```

Distance matrix + 150 miles

Forest cost

Forest structure by node #
(2 connects to 3, 3 connects
to 4, etc.)

CW output:

```
INPUT LAT, LONG, CLUSTER
38.15  121.55  1
47.08  122.28  1
42.09  121.44  1
43.33  116.13  1
43.02  115.52  2
43.02  115.52  2
  0
 763    0
419 495    0
621 541 445    0
607 578 454 189    0
607 578 454 189    0    0
ARCS IN THE SOLUTION
  5  4
  4  2
  3  2
  3  1
  5  1
  6  1 TWICE
THE TOTAL COST=
3465
```

```
1 SUU (only depot selected)
2 TCM
3 LMT
4 BOI
5 MUO
6 MUO
```

Distance Matrix

Route structure by node #
(5 connects to 4, 4 connects
to 2, etc.)

Route cost in statute miles.
note that 150 * the number
of legs (7 in this case)
must be subtracted for
actual mileage.

Heuristic error:
 $(3465-3410)/3410 = 1.61\%$

Region 1 with 2 depots forced.

Laporte output:

```
"REG12"
128, 63, 9554.0000
"X12", 0.0000, 764.0000
"X13", 0.0000, 496.0000
"X14", 1.0000, 541.0000
"X15", 1.0000, 0.0000
"X16", 0.0000, 764.0000
"X17", 0.0000, 578.0000
"X18", 0.0000, 578.0000
"X23", 0.0000, 419.0000
"X24", 0.0000, 621.0000
"X25", 0.0000, 764.0000
"X26", 1.0000, 0.0000
"X27", 1.0000, 608.0000
"X28", 0.0000, 608.0000
"X34", 0.0000, 445.0000
"X35", 0.0000, 496.0000
"X36", 0.0000, 419.0000
"X37", 0.0000, 454.0000
"X38", 0.0000, 454.0000
"X45", 0.0000, 541.0000
"X46", 0.0000, 621.0000
"X47", 0.0000, 190.0000
"X48", 1.0000, 190.0000
"X56", 0.0000, 764.0000
"X57", 0.0000, 578.0000
"X58", 0.0000, 578.0000
"X67", 0.0000, 608.0000
"X68", 0.0000, 608.0000
"X21", 0.0000, 764.0000
"X31", 0.0000, 496.0000
"X41", 0.0000, 541.0000
"X51", 1.0000, 0.0000
"X61", 0.0000, 764.0000
"X71", 0.0000, 578.0000
"X81", 1.0000, 578.0000
"X32", 1.0000, 419.0000
"X42", 0.0000, 621.0000
"X52", 0.0000, 764.0000
"X62", 1.0000, 0.0000
"X72", 0.0000, 608.0000
"X82", 0.0000, 608.0000
"X43", 0.0000, 445.0000
"X53", 0.0000, 496.0000
"X63", 0.0000, 419.0000
"X73", 1.0000, 454.0000
"X83", 0.0000, 454.0000
"X54", 0.0000, 541.0000
"X64", 0.0000, 621.0000
```

Output explanation:

Comparative cost
(without depots) is 9554
- 2(3382)=2790.

Node assignments:

1,5 TCM
2,6 SUU
3 LMT
4 BOI
7,8 MUO

"X74	",	0.0000,	190.0000
"X84	",	0.0000,	190.0000
"X65	",	0.0000,	764.0000
"X75	",	0.0000,	573.0000
"X85	",	0.0000,	578.0000
"X76	",	0.0000,	608.0000
"X86	",	0.0000,	608.0000
"Y1	",	1.0000,	3382.0000
"Y2	",	1.0000,	3382.0000
"M1	",	2.0000,	0.0000
"M2	",	2.0000,	0.0000
"D3	",	2181.0000,	0.0000
"D4	",	541.0000,	0.0000
"D5	",	684.0000,	0.0000
"D6	",	2520.0000,	0.0000
"D7	",	1727.0000,	0.0000

The constraint output is
deleted for brevity.

Region 1 with 2 depots.

MSF output:

```
47.08    122.28    1
38.15    121.55    1
42.09    121.44    1
43.33    116.13    1
43.02    115.52    2
  0
 763      0
 495  419      0
 541  621  445      0
 578  607  454  189      0
BEST WEIGHT=                      3389
EMANATING NODES ON TOP
INCIDENT NODES BELOW
  2      3      4
  3      4      5
```

Output explanation (where
different from previous):

```
1 TCM
2 SUU
3 LMT
4 BOI
5 MUO
```

SUU is the only depot with
emanating routes.

CW output:

SUU only is run since TCM
depot has no routes.

```
INPUT LAT, LONG, CLUSTER
38.15    121.55    1
42.09    121.44    1
43.33    116.13    1
43.02    115.52    2
43.02    115.52    2
  0
 419      0
 621  445      0
 607  454  189      0
 607  454  189      0      0
ARCS IN THE SOLUTION
  4      3
  3      2
  2      1
  4      1
  5      1 TWICE
THE TOTAL COST=
2874
```

Heuristic error:
(2874-2790)/2790 = 3%

Region 2 with optimal depot:

Laporte formulation output:

Output explanation
(where different from
previous):

"REG21 "	131, 66, 6545.0000	
"X12 "	0.0000,	778.0000
"X13 "	1.0000,	402.0000
"X14 "	0.0000,	705.0000
"X15 "	0.0000,	0.0000
"X16 "	0.0000,	778.0000
"X17 "	0.0000,	517.0000
"X18 "	1.0000,	696.0000
"X23 "	0.0000,	877.0000
"X24 "	0.0000,	331.0000
"X25 "	0.0000,	778.0000
"X26 "	0.0000,	0.0000
"X27 "	0.0000,	410.0000
"X28 "	0.0000,	437.0000
"X34 "	0.0000,	863.0000
"X35 "	1.0000,	402.0000
"X36 "	0.0000,	877.0000
"X37 "	0.0000,	639.0000
"X38 "	0.0000,	692.0000
"X45 "	0.0000,	705.0000
"X46 "	0.0000,	331.0000
"X47 "	1.0000,	378.0000
"X48 "	0.0000,	556.0000
"X56 "	0.0000,	778.0000
"X57 "	0.0000,	517.0000
"X58 "	0.0000,	696.0000
"X67 "	0.0000,	410.0000
"X68 "	0.0000,	437.0000
"X78 "	0.0000,	424.0000
"X21 "	0.0000,	778.0000
"X31 "	0.0000,	402.0000
"X41 "	0.0000,	705.0000
"X51 "	1.0000,	0.0000
"X61 "	0.0000,	778.0000
"X71 "	1.0000,	517.0000
"X81 "	0.0000,	696.0000
"X32 "	0.0000,	877.0000
"X42 "	0.0000,	331.0000
"X52 "	0.0000,	778.0000
"X62 "	0.0000,	0.0000
"X72 "	0.0000,	410.0000
"X82 "	0.0000,	437.0000
"X43 "	0.0000,	863.0000
"X53 "	0.0000,	402.0000
"X63 "	0.0000,	877.0000
"X73 "	0.0000,	639.0000
"X83 "	0.0000,	692.0000
"X54 "	0.0000,	705.0000

Comparative cost is
6545-3382 = 3163

Node assignment:

1,5 OFF
2,5 FFO
3 IAB
4 BTL
7 BMI
8 HOP

"X64	",	1.0000,	331.0000	
"X74	",	0.0000,	378.0000	
"X84	",	0.0000,	556.0000	
"X65	",	0.0000,	778.0000	
"X75	",	0.0000,	517.0000	
"X85	",	0.0000,	696.0000	
"X76	",	0.0000,	410.0000	
"X86	",	1.0000,	437.0000	
"X87	",	0.0000,	424.0000	
"Y1	",	1.0000,	3382.0000	
"Y2	",	0.0000,	3382.0000	
"M1	",	2.0000,	0.0000	
"M2	",	0.0000,	0.0000	
"D3	",	2080.0000,	0.0000	
"D4	",	1644.0000,	0.0000	
"D5	",	2182.0000,	0.0000	
"D6	",	1015.0000,	0.0000	
"D7	",	2022.0000,	0.0000	Constraint activity
"D8	",	578.0000,	0.0000	deleted for brevity.

Region 2 with 1 depot.

MSF output:

41.07	95.54	1
39.50	84.03	1
37.37	97.16	1
42.18	85.14	1
40.29	88.55	1
36.40	87.29	1

0

778 0

402 877 0

705 331 863 0

517 410 639 378 0

696 437 692 556 424 0

BEST WEIGHT= 3981

EMANATING NODES ON TOP

INCIDENT NODES BELOW

1	1	5	4	5
---	---	---	---	---

3	5	4	2	6
---	---	---	---	---

Output explanation where
different:

1 OFF

2 FFO

3 IAB

4 BTL

5 BMI

6 HOP

CW output:

INPUT LAT, LONG, CLUSTER

41.07	95.54	1
-------	-------	---

39.50	84.03	1
-------	-------	---

37.37	97.16	1
-------	-------	---

42.18	85.14	1
-------	-------	---

40.29	88.55	1
-------	-------	---

36.40	87.29	1
-------	-------	---

0

778 0

402 877 0

705 331 863 0

517 410 639 378 0

696 437 692 556 424 0

ARCS IN THE SOLUTION

4 2

6 2

5 4

3 1 TWICE

5 1

6 1

THE TOTAL COST=

3163

Heuristic error:

0%

Region 2 with 2 depots forced:

Laporte formulation output:

Output explanation as
necessary:

"REG22"

130,	66,	9138.0000	
"X12	"	0.0000,	778.0000
"X13	"	0.0000,	402.0000
"X14	"	0.0000,	705.0000
"X15	"	1.0000,	0.0000
"X16	"	0.0000,	778.0000
"X17	"	0.0000,	517.0000
"X18	"	0.0000,	696.0000
"X23	"	0.0000,	877.0000
"X24	"	1.0000,	331.0000
"X25	"	0.0000,	778.0000
"X26	"	0.0000,	0.0000
"X27	"	0.0000,	410.0000
"X28	"	0.0000,	437.0000
"X34	"	0.0000,	863.0000
"X35	"	0.0000,	402.0000
"X36	"	0.0000,	877.0000
"X37	"	0.0000,	639.0000
"X38	"	0.0000,	692.0000
"X45	"	0.0000,	705.0000
"X46	"	0.0000,	331.0000
"X47	"	1.0000,	378.0000
"X48	"	0.0000,	556.0000
"X56	"	0.0000,	778.0000
"X57	"	0.0000,	517.0000
"X58	"	0.0000,	696.0000
"X67	"	0.0000,	410.0000
"X68	"	0.0000,	437.0000
"X78	"	1.0000,	424.0000
"X21	"	0.0000,	778.0000
"X31	"	1.0000,	402.0000
"X41	"	0.0000,	705.0000
"X51	"	0.0000,	0.0000
"X61	"	0.0000,	778.0000
"X71	"	0.0000,	517.0000
"X81	"	0.0000,	696.0000
"X32	"	0.0000,	877.0000
"X42	"	0.0000,	331.0000
"X52	"	0.0000,	778.0000
"X62	"	1.0000,	0.0000
"X72	"	0.0000,	410.0000
"X82	"	0.0000,	437.0000
"X43	"	0.0000,	863.0000
"X53	"	1.0000,	402.0000
"X63	"	0.0000,	877.0000
"X73	"	0.0000,	639.0000
"X83	"	0.0000,	692.0000
"X54	"	0.0000,	705.0000

Comparative cost is
9138-6764 = 2374

Node assignment:

1,5 OFF
2,6 FFO
3 IAB
4 BTL
7 BMI
8 HOP

"X64	",	0.0000,	331.0000	
"X74	",	0.0000,	378.0000	
"X84	",	0.0000,	556.0000	
"X65	",	0.0000,	778.0000	
"X75	",	0.0000,	517.0000	
"X85	",	0.0000,	696.0000	
"X76	",	0.0000,	410.0000	
"X86	",	1.0000,	437.0000	
"X87	",	0.0000,	424.0000	
"Y1	",	1.0000,	3382.0000	
"Y2	",	1.0000,	3382.0000	
"M1	",	1.0000,	0.0000	
"M2	",	1.0000,	0.0000	
"D3	",	2104.0000,	0.0000	
"D4	",	621.0000,	0.0000	
"D5	",	38.0000,	0.0000	
"D6	",	1860.0000,	0.0000	
"D7	",	999.0000,	0.0000	Constraint activity
"D8	",	1423.0000,	0.0000	deleted for brevity.

Region 2 with 2 depots.

MSF output:

41.07	95.54	1
39.50	84.03	1
37.37	97.16	1
42.18	85.14	1
40.29	88.55	1
36.40	87.29	1

0

778 0

402 877 0

705 331 863 0

517 410 639 378 0

696 437 692 556 424 0

BEST WEIGHT= 2575

EMANATING NODES ON TOP

INCIDENT NODES BELOW

2	4	1	5
---	---	---	---

4	5	3	6
---	---	---	---

Output explanation as required:

1 OFF

2 FFO

3 IAB

4 BTL

5 BMI

6 HOP

FFO serves 3 bases

OFF serves 1 base

CW output:

INPUT LAT, LONG, CLUSTER

39.50	84.03	1
-------	-------	---

42.18	85.14	1
-------	-------	---

40.29	88.55	1
-------	-------	---

36.40	87.29	1
-------	-------	---

0

331 0

410 378 0

437 556 424 0

ARCS IN THE SOLUTION

4	3
---	---

3	2
---	---

2	1
---	---

4	1
---	---

THE TOTAL COST=

1570

1 FFO

2 BTL

3 BMI

4 HOP

Routing from OFF to
IAB and return is
trivial and = 804. Total
= 804 + 1570 = 2374

Heuristic error:

0%

Region 3 with optimal depot.

Laporte formulation output:

Explanation as
necessary:

"REG31"

129,	63,	6071.0000	
"X12	"	0.0000,	357.0000
"X13	"	0.0000,	319.0000
"X14	"	0.0000,	345.0000
"X15	"	0.0000,	0.0000
"X16	"	0.0000,	357.0000
"X17	"	0.0000,	528.0000
"X18	"	0.0000,	528.0000
"X23	"	1.0000,	496.0000
"X24	"	0.0000,	546.0000
"X25	"	0.0000,	357.0000
"X26	"	1.0000,	0.0000
"X27	"	1.0000,	323.0000
"X28	"	0.0000,	323.0000
"X34	"	1.0000,	351.0000
"X35	"	0.0000,	319.0000
"X36	"	0.0000,	496.0000
"X37	"	0.0000,	668.0000
"X38	"	0.0000,	668.0000
"X45	"	1.0000,	345.0000
"X46	"	0.0000,	546.0000
"X47	"	0.0000,	711.0000
"X48	"	0.0000,	711.0000
"X56	"	0.0000,	357.0000
"X57	"	0.0000,	528.0000
"X58	"	1.0000,	528.0000
"X67	"	0.0000,	323.0000
"X68	"	0.0000,	323.0000
"X21	"	0.0000,	357.0000
"X31	"	0.0000,	319.0000
"X41	"	0.0000,	345.0000
"X51	"	0.0000,	0.0000
"X61	"	0.0000,	357.0000
"X71	"	0.0000,	528.0000
"X81	"	0.0000,	528.0000
"X32	"	0.0000,	496.0000
"X42	"	0.0000,	546.0000
"X52	"	0.0000,	357.0000
"X62	"	1.0000,	0.0000
"X72	"	1.0000,	323.0000
"X82	"	1.0000,	323.0000
"X43	"	0.0000,	351.0000
"X53	"	0.0000,	319.0000
"X63	"	0.0000,	496.0000
"X73	"	0.0000,	668.0000
"X83	"	0.0000,	668.0000
"X54	"	0.0000,	345.0000
"X64	"	0.0000,	546.0000

Comparative is 6071-3382
= 2689.

Node assignment:

1,5 CHS
2,6 NIP
3 CLT
4 NCA
7,8 MCF

"X74	",	0.0000,	711.0000	
"X84	",	0.0000,	711.0000	
"X65	",	0.0000,	357.0000	
"X75	",	0.0000,	528.0000	
"X85	",	0.0000,	528.0000	
"X76	",	0.0000,	323.0000	
"X86	",	0.0000,	323.0000	
"Y1	",	0.0000,	3382.0000	
"Y2	",	1.0000,	3382.0000	
"M1	",	0.0000,	0.0000	
"M2	",	3.0000,	0.0000	
"D3	",	496.0000,	0.0000	
"D4	",	1404.0000,	0.0000	
"D5	",	1749.0000,	0.0000	
"D6	",	205.0000,	0.0000	Constraint activity
"D7	",	2277.0000,	0.0000	deleted for brevity.

Region 3 with 1 depot.

MSF output:

32.53	80.02	1
30.14	81.41	1
35.13	80.56	1
34.43	77.26	1
27.50	82.31	2

0

357 0

319 496 0

345 546 351 0

528 323 668 711 0

BEST WEIGHT= 2381

EMANATING NODES ON TOP

INCIDENT NODES BELOW

1	1	1	2
3	4	2	5

Explanation as
necessary:

1	CHS
2	NIP
3	CLT
4	NCA
5	MCF

CHS chosen

CW output:

INPUT LAT, LONG, CLUSTER

32.53	80.02	1
30.14	81.41	1
35.13	80.56	1
34.43	77.26	1
27.50	82.31	2
27.50	82.31	2

1	CHS
2	NIP
3	CLT
4	NCA
5	MCF
6	MCF

0

357 0

319 496 0

345 546 351 0

528 323 668 711 0

528 323 668 711 0 0

ARCS IN THE SOLUTION

5 2

4 3

3 2

4 1

5 1

6 1 TWICE

THE TOTAL COST=

3099

Heuristic error:

(3099-2689)/2689 =

15.25%

Region 3 with 2 depots forced.

Laporte formulation output:

Explanation as
necessary:

"REG32"

128,	63,	9071.0000		Comparative cost is
"X12	"	0.0000,	357.0000	9071-6764 = 2307
"X13	"	1.0000,	319.0000	
"X14	"	0.0000,	345.0000	Node assignment:
"X15	"	1.0000,	0.0000	1,5 CHS
"X16	"	0.0000,	357.0000	2,6 NIP
"X17	"	0.0000,	528.0000	3 CLT
"X18	"	0.0000,	528.0000	4 NCA
"X23	"	0.0000,	496.0000	7,8 MCF
"X24	"	0.0000,	546.0000	
"X25	"	0.0000,	357.0000	
"X26	"	1.0000,	0.0000	
"X27	"	1.0000,	323.0000	
"X28	"	0.0000,	323.0000	
"X34	"	1.0000,	351.0000	
"X35	"	0.0000,	319.0000	
"X36	"	0.0000,	496.0000	
"X37	"	0.0000,	668.0000	
"X38	"	0.0000,	668.0000	
"X45	"	0.0000,	345.0000	
"X46	"	0.0000,	546.0000	
"X47	"	0.0000,	711.0000	
"X48	"	0.0000,	711.0000	
"X56	"	0.0000,	357.0000	
"X57	"	0.0000,	528.0000	
"X58	"	0.0000,	528.0000	
"X67	"	0.0000,	323.0000	
"X68	"	1.0000,	323.0000	
"X21	"	0.0000,	357.0000	
"X31	"	0.0000,	319.0000	
"X41	"	1.0000,	345.0000	
"X51	"	1.0000,	0.0000	
"X61	"	0.0000,	357.0000	
"X71	"	0.0000,	528.0000	
"X81	"	0.0000,	528.0000	
"X32	"	0.0000,	496.0000	
"X42	"	0.0000,	546.0000	
"X52	"	0.0000,	357.0000	
"X62	"	0.0000,	0.0000	
"X72	"	1.0000,	323.0000	
"X82	"	1.0000,	323.0000	
"X43	"	0.0000,	351.0000	
"X53	"	0.0000,	319.0000	
"X63	"	0.0000,	496.0000	
"X73	"	0.0000,	668.0000	
"X83	"	0.0000,	668.0000	
"X54	"	0.0000,	345.0000	
"X64	"	0.0000,	546.0000	

"X74	",	0.0000,	711.0000	
"X84	",	0.0000,	711.0000	
"X65	",	0.0000,	357.0000	
"X75	",	0.0000,	528.0000	
"X85	",	0.0000,	528.0000	
"X76	",	0.0000,	323.0000	
"X86	",	0.0000,	323.0000	
"Y1	",	1.0000,	3382.0000	
"Y2	",	1.0000,	3382.0000	
"M1	",	2.0000,	0.0000	
"M2	",	2.0000,	0.0000	
"D3	",	1904.0000,	0.0000	
"D4	",	2255.0000,	0.0000	
"D5	",	0.0000,	0.0000	
"D6	",	201.0000,	0.0000	Constraint activity
"D7	",	729.0000,	0.0000	deleted for brevity.

Region 3 with 2 depots.

MSF output:

32.53	80.02	1
30.14	81.41	1
35.13	80.56	1
34.43	77.26	1
27.50	82.31	2

Explanation as
necessary:

1	CHS
2	NIP
3	CLT
4	NCA
5	MCF

0				
357	0			
319	496	0		
345	546	351	0	
528	323	668	711	0

BEST WEIGHT= 1310

EMANATING NODES ON TOP

INCIDENT NODES BELOW

1	2	1
3	5	4

CW output is not included as the routing from CHS - CLT -
NCA - CHS is trivial (equals 1015), and 2 round trips from
CHS to MCF equal 1292. The total is 2307, which is 0% from
optimal.

Appendix D: Spanning Forest Data Set

1	2	3	4
38.15	121.55	1	SUU/F-1
29.22	98.35	4	SKF/F-2
39.11	76.40	12	BWI/F-3
47.08	122.28	2	TCM/C-4
32.41	117.12	1	NZY/C-5
39.46	104.53	2	DEN/C-6
41.07	95.54	4	OFF/C-7
39.50	84.03	12	FFO/C-8
42.09	70.56	2	NZW/C-9
36.56	76.17	2	NGU/C-10
32.53	80.02	2	CHS/C-11
30.14	81.41	2	NIP/C-12
40.47	111.58	2	SLC/C-13
36.14	115.02	1	LSV/C-14
33.32	112.23	1	LUF/C-15
35.03	106.34	1	ABQ/C-16
31.48	106.23	1	ELP/C-17
32.46	97.26	2	FWH/C-18
35.25	97.23	2	TIK/C-19
34.54	92.08	1	LRF/C-20
35.02	89.58	1	MEM/C-21
37.37	97.16	2	IAB/C-22
38.32	89.51	2	BLV/C-23
42.05	87.49	1	NBU/C-24
38.10	85.44	2	SDF/C-25
43.14	75.24	2	RME/C-26
29.50	90.01	1	NBG/C-27
27.50	82.31	2	MCF/C-28
25.29	80.23	2	HST/C-29
33.54	84.31	2	NCQ/C-30
38.40	121.23	2	MCC-31
37.17	120.31	2	MCE-32
36.20	119.57	2	NLC-33
37.53	121.14	2	SCK-34
36.46	119.43	2	FAT-35
36.35	121.50	2	MRY-36
42.09	121.44	1	LMT-37
39.29	119.46	1	RNO-38
39.24	118.41	1	NFL-39
46.34	120.32	2	YKM-40
47.37	117.31	2	GEG-41
46.15	119.06	1	PSC-42
43.33	116.13	1	BOI-43
43.02	115.52	1	MUO-44
32.50	115.40	1	NJK-45
32.39	114.36	1	NYL-46
35.41	117.41	1	NID-47
34.17	116.10	1	NXP-48
34.51	116.47	1	DAG-49

34.12	119.12	1	OXR-50
34.54	117.52	1	EDW-51
34.43	120.34	2	VBG-52
41.09	104.49	2	CYS-53
44.08	103.06	2	RCA-54
48.24	101.21	2	MIB-55
47.57	97.24	2	RDR-56
47.30	111.11	2	GFA-57
43.31	112.04	1	IDA-58
45.48	108.32	1	BIL-59
46.36	111.59	1	HLN-60
49.54	97.14	1	YWG-61
34.39	98.24	2	FSI-62
32.30	93.40	2	BAD-63
31.21	100.29	2	SJT-64
32.25	99.51	2	DYS-65
31.04	97.50	2	GRK-66
30.12	97.41	2	BSM-67
34.40	99.16	1	LTS-68
32.19	90.05	1	JAN-69
31.19	92.32	1	AEX-70
35.20	94.22	1	FSM-71
34.29	93.06	1	HOT-72
29.36	95.09	1	EFD-73
32.51	106.06	1	HMN-74
32.09	110.52	1	DMA-75
34.23	103.19	1	CVS-76
29.22	100.47	1	DLV-77
33.59	98.29	1	SPS-78
33.35	102.02	1	REE-79
35.13	101.43	1	AMA-80
41.32	93.39	1	DSM-81
41.53	91.42	1	CID-82
41.26	90.30	1	MLI-83
43.57	90.44	1	CMY-84
44.53	93.13	1	MSP-85
43.34	96.44	1	FSD-86
42.24	96.23	1	SUX-87
39.22	94.54	1	FLV-88
39.03	96.46	1	FRI-89
38.51	94.33	1	GVW-90
38.57	95.39	1	FOE-91
37.44	92.08	1	TBN-92
35.58	89.57	2	BYH-93
38.44	93.33	2	SZL-94
38.34	90.09	4	CPS-95
42.57	87.53	1	MKE-96
42.18	85.14	1	BTL-97
41.35	83.48	1	TOL-98
41.01	83.41	1	FDY-99
41.25	81.51	1	CLE-100
40.29	80.14	1	PIT-101
39.49	82.56	1	LCK-102

40.49	82.30	1	MFD-103
40.58	85.11	1	FWA-104
40.38	86.09	1	GUS-105
39.27	87.18	1	HUF-106
40.29	88.55	1	BMI-107
39.09	86.37	1	BMG-108
39.06	84.25	1	LUK-109
36.40	87.29	1	HOP-110
35.24	86.05	1	TUH-111
35.49	84.00	1	TYS-112
38.22	81.36	1	CUW-113
41.35	71.25	2	OQW-114
41.04	73.42	2	HPN-115
43.07	76.06	2	SYR-116
44.03	75.44	2	GTB-117
42.45	73.48	2	ALB-118
42.11	72.31	2	CEF-119
40.44	73.25	2	FRG-120
41.30	74.06	2	SWF-121
42.12	75.59	2	BGM-122
42.56	78.44	2	BUF-123
43.07	77.40	2	ROC-124
41.16	72.53	2	AVN-125
41.19	72.02	2	GON-126
41.56	72.41	2	BDL-127
44.39	73.28	2	PBG-128
44.28	73.09	2	BTU-129
42.56	71.26	2	MHT-130
43.04	70.49	2	PSM-131
43.53	69.56	2	NHZ-132
44.48	68.50	2	BGR-133
46.57	67.53	2	LIZ-134
41.40	70.31	2	FMH-135
37.05	76.21	12	LFI-136
34.40	86.41	4	HUA-137
38.08	78.27	2	CHO-138
38.17	76.24	2	NHK-139
38.15	78.53	2	SHD-140
37.19	79.52	2	ROA-141
39.38	79.54	2	MGW-142
39.42	77.43	2	HGR-143
40.51	77.51	2	UNV-144
41.20	75.43	2	AVP-145
40.11	76.45	2	MDT-146
33.40	78.55	2	MYR-147
33.57	80.28	2	SSC-148
33.22	81.58	2	AGS-149
33.39	88.27	2	CBM-150
33.33	86.45	2	BHM-151
33.35	85.51	2	ANB-152
32.28	80.43	2	NBC-153
31.53	81.34	2	LHW-154
32.38	83.35	2	WRB-155

32.20	84.59	2	LSF-156
32.22	86.21	2	MXF-157
32.20	88.44	2	MEI-158
31.16	85.42	2	OZR-159
31.32	84.12	2	ABY-160
24.35	91.41	2	NOX-161
26.41	80.06	2	PBI-162
28.14	80.36	2	COF-163
28.25	81.19	2	MCO-164
30.24	88.55	2	BIX-165
30.21	87.19	2	NPA-166
30.29	86.31	2	VPS-167
30.04	85.34	2	PAM-168
30.58	83.11	1	VAD-169
30.23	84.21	1	TLH-170
34.54	76.53	2	NKT-171
34.43	77.26	2	NCA-172
34.54	82.13	2	GSP-173
35.26	82.32	2	AVL-174
36.29	82.25	2	TRI-175
37.31	77.19	2	RIC-176
35.20	77.58	2	GSB-177
35.10	79.01	2	POB-178
35.13	80.56	2	CLT-179
36.06	79.56	2	GSO-180
35.53	78.47	2	RDU-181

Columns:

- 1 Latitude
- 2 Longitude
- 3 Frequency in visits per 2 weeks
- 4 ICAO and program assignment number

Appendix E: MSF and CW Output

11 Depot Model

MSF:

Note, the number assignments are given in Appendix D.

BEST WEIGHT= 279481

DEPOTS=

1 2 3 5 7 8 9 11 12 20 26

EMINATING NODES ON TOP

INCIDENT NODES BELOW

26	9	1	1	9	114	126	125	115	115
116	135	31	34	114	126	125	115	120	121
125	127	11	8	34	32	35	26	8	9
127	119	153	109	32	35	33	117	102	130
130	20	116	122	3	153	3	143	131	102
131	72	122	145	139	154	143	146	132	103
103	103	99	139	176	136	146	176	138	119
100	99	98	176	136	10	144	138	140	118
11	2	67	99	104	116	124	132	11	32
148	67	66	104	105	124	123	133	147	36
140	141	180	181	181	177	172	180	179	173
141	180	181	178	177	172	171	179	173	174
174	174	98	5	45	72	7	87	109	25
175	112	97	45	46	71	87	86	25	108
108	153	12	169	160	156	160	170	168	167
106	149	169	160	156	157	170	168	167	166
167	157	151	151	137	152	160	166	165	151
159	151	152	137	111	30	155	165	27	150
150	158	31	38	45	48	49	51	51	50
158	69	38	39	48	49	51	47	50	52
100	101	106	107	83	82	141	111	66	18
101	142	107	83	82	81	113	110	18	78
78	62	62	117	128	20	21	107	24	12
62	68	19	128	129	21	93	24	96	164
164	164	163	162	29	7	88	88	90	91
163	28	162	29	161	88	90	91	94	89
89	94	92	95	2	78	65	49	72	63

22	92	95	23	77	65	64	14	63	70
46	15	68	80	76	82	84	133	67	76
15	75	80	76	79	84	85	134	73	16
16	74	38	39	44	44	58	58	60	43
74	17	37	44	43	58	13	60	57	42
42	40	42	86	56	56	55	54	53	54
40	4	41	56	61	55	54	53	6	59

CW for 11 Depot:

SKF data file.

1	2	3	4	5	6
29.22	98.35	1	SKF/F-2	1	KELLY
31.48	106.23	2	ELP/C-17	2,3	FT BLISS
32.46	97.26	4	FWH/C-18	4,5,6,7	CARSWELL
35.25	97.23	4	TIK/C-19	8,9,10,11	TINKER
35.03	106.34	2	ABQ/C-16	12,13	KIRTLAND
34.39	98.24	4	FSI-62	14,15,16,17	FT SILL
31.21	100.29	4	SJT-64	18,19,20,21	GOODFELLOW
32.25	99.51	4	DYS-65	22,23,24,25	DYESS
31.04	97.50	4	GRK-66	26,27,28,29	FT HOOD
30.12	97.41	4	BSM-67	30,31,32,33	BERGSTROM
34.40	99.16	2	LTS-68	34,35	ALTUS
29.36	95.09	2	EFD-73	36,37	ELLINGTON
32.51	106.06	2	HMN-74	38,39	HOLLOMAN
34.23	103.19	2	CVS-76	40,41	CANNON
29.22	100.47	1	DLF-77	42	LAUGHLIN
33.59	98.29	1	SPS-78	43	SHEPPARD
33.35	102.02	1	REE-79	44	REESE
35.13	101.43	1	AMA-80	45	AMARILLO

Column explanation for all CW data files:

1	Latitude
2	Longitude
3	Visits per <u>4 week</u> period
4	ICAO Identifier and CONUS system number
5	Number assignments for CW runs
6	Name

SKF output file:

ARCS IN THE SOLUTION

38	12
39	13
38	2

39 3
 40 12
 41 13
 45 40
 14 8
 15 9
 16 10
 17 11
 44 41
 34 14
 35 15
 43 16
 8 4
 9 5
 10 6
 11 7
 45 22
 34 23
 35 24
 44 25
 23 18
 24 19
 20 17
 43 21
 26 4
 27 5
 28 6
 29 7
 30 26
 31 27
 32 28
 33 29
 36 32
 37 33
 42 2
 3 1
 18 1
 19 1
 20 1
 21 1
 22 1
 25 1
 30 1
 31 1
 36 1
 37 1
 42 1

THE TOTAL COST=
 14505

Cost explanation:

-Run was made over 4 week period

-50 legs (arcs) in solution

Weekly milage =

$$\frac{(14505 - 150 * 50)}{4} = 1751$$

Example output interpretation is done by matching
 ICAO's with solution arcs:

Route 1: SKF-DLF-ELP-HMN-ABQ-CVS-AMA-DYS-SKF
 1 42 2 38 12 40 45 22 1
 Route 2: SKF-ELP-HMN-ABQ-CVS-AMA-DYS-SKF
 1 3 39 13 41 44 25 1
 Route 3: SKF-BSM-GRK-FWH-TIK-FSI-LTS-DYS-SJT-SKF
 1 30 26 4 8 14 34 23 18 1
 Route 4: SKF-BSM-GRK-FWH-TIK-FSI-LTS-DYS-SJT-SKF
 1 31 27 5 9 15 35 24 19 1
 Route 5: SKF-EFD-BSM-GRK-FWH-TIK-FSI-SPS-SJT-SKF
 1 36 32 28 6 10 16 43 21 1
 Route 6: SKF-EFD-BSM-GRK-FWH-TIK-FSI-SJT-SKF
 1 37 33 29 7 11 17 20 1

CHS data file (11 depot):

Frequency based on weekly rate.

32.53	80.02	1	CHS/C-11	1	CHARLESTON
33.40	78.55	1	MYR-147	2	MYRTLE BEACH
33.57	80.23	1	SSC-148	3	SHAW
33.22	81.58	1	AGS-149	4	FT GORDON
32.28	80.43	1	NBC-153	5	BEAUFORT
31.53	81.34	1	LHW-154	6	FT STEWART

CHS output file.

ARCS IN THE SOLUTION

6 4
 4 3
 6 5
 3 2
 2 1
 5 1

Cost explanation:
 -6 arcs in solution
 Weekly milage =

THE TOTAL COST=
 1387

1387-(6*150)= 487

Example output interpretation:

Route 1: CHS-NBC-LWH-AGS-SSC-MYR-CHS
 1 5 6 4 3 2 1

BWI data file (11 depot):

Frequency based on 2 week rate.

39.11	76.40	1	BWI/F-3	1	BALTIMORE
36.56	76.17	2	NGU/C-10	2,3	NORFOLK
35.49	84.00	1	TYS-112	4	KNOXVILLE
38.22	81.36	1	CUW-113	5	CHARLESTON WV
37.05	76.21	12	LFI-136	6-17	LANGLEY

38.08	78.27	2	CHO-138	18,19	CHARLOTTESVILLE
38.17	76.24	2	NHK-139	20,21	PAX RIVER
38.15	78.53	2	SHD-140	22,23	SHENENDOAH
37.19	79.58	2	ROA-141	24,25	ROANOKE
39.42	77.43	2	HGR-143	26,27	HAGERSTOWN
40.51	77.51	2	UNV-144	28,29	STATE COLLEGE
40.11	76.45	2	MDT-146	30,31	HARRISBURG
34.54	76.53	2	NKT-171	32,33	CHERRY POINT
34.43	77.26	2	NCA-172	34,35	JACKSONVILLE
34.54	82.13	2	GSP-173	36,37	GREENSVILLE
35.26	82.32	2	AVL-174	38,39	ASHEVILLE
36.29	82.25	2	TRI-175	40,41	BRISTOL
37.31	77.19	2	RIC-176	42,43	RICHMOND
35.20	77.58	2	GSB-177	44,45	GOLDSBORO
35.10	79.01	2	POB-178	46,47	POPE
35.13	80.56	2	CLT-179	48,49	CHARLOTTE
36.06	79.56	2	GSO-180	50,51	GREENSBORO
35.53	78.47	2	RDU-181	52,53	RALIEGH

BWI output file:

ARCS IN THE SOLUTION

38 36
 39 37
 38 4
 40 4
 48 36
 49 37
 41 39
 34 32
 35 33
 48 46
 49 47
 44 34
 45 35
 47 44
 52 46
 50 40
 53 45
 53 51
 51 24
 24 5
 33 2
 6 2
 7 3
 41 22
 25 23
 25 18
 42 3
 43 8
 42 18
 43 19
 20 7

21 8
 30 28
 31 29
 28 26
 29 27
 26 23
 27 19
 5 1
 6 1
 9 1 TWICE
 10 1 TWICE
 11 1 TWICE
 12 1 TWICE
 13 1 TWICE
 14 1 TWICE
 15 1 TWICE
 16 1 TWICE
 17 1 TWICE
 20 1
 21 1
 22 1
 30 1
 31 1
 32 1
 50 1
 52 1
 THE TOTAL COST=
 17177

Cost explanation:
 -Run was made over
 2 week period
 -66 arcs in solution

Weekly milage=

$$\frac{17177 - (150 * 66)}{2} = 3638$$

 SUU data file (11 depot):

Frequency based on 2 week rate.

38.15	121.55	1	SUU/F-1	1	TRAVIS
38.40	121.23	2	MCC-31	2,3	MCCLELLAN
37.17	120.31	2	MCE-32	4,5	MERCED
36.20	119.57	2	NLC-33	6,7	LEMOORE
37.53	121.14	2	SCK-34	8,9	STOCKTON
36.46	119.43	2	FAT-35	10,11	FRESNO
36.35	121.50	2	MRY-36	12,13	MONTERRY
42.09	121.44	1	LMT-37	14	KLAMATH FALLS
39.29	119.46	1	RNO-38	15	RENO
39.24	118.41	1	NFL-39	16	FALLON
40.47	111.58	2	SLC/C-13	17,18	SALT LAKE CITY
47.08	122.28	2	TCM/C-4	19,20	MCCHORD
46.34	120.32	2	YKM-40	21,22	YAKIMA
47.37	117.31	2	GEG-41	23,24	SPOKANE
46.15	119.06	1	PSC-42	25	PASCO
43.33	116.13	1	BOI-43	26	BOISE
43.02	115.52	1	MUO-44	27	MT HOME
47.30	111.11	2	GFA-57	28,29	MALMSTROM
43.31	112.04	1	IDA-58	30	IDAHO FALLS

46.36 111.59 1 HLN-60 31 HELENA

SUU output file:

ARCS IN THE SOLUTION

31 28
28 23
29 24
30 29
25 23
21 19
22 20
27 26
27 17
21 18
20 14
17 16
10 6
11 7
26 15
10 4
11 5
12 6
13 7
8 4
9 5
15 2
22 3
2 1
3 1
8 1
9 1
12 1
13 1
14 1
16 1
18 1
19 1
24 1
25 1
30 1
31 1

THE TOTAL COST=
14557

Cost explanation:
-Run was made over 2 week
period.
-37 arcs in solution

Weekly milage:
 $\frac{14557 - (150 * 37)}{2} = 4504$

NZY data file (11 depot):

Frequency based on 2 week rate:

32.41	117.12	1	NZY/C-5	1	NORTH ISLAND
36.14	115.02	1	LSV/C-14	2	LAS VEGAS
33.32	112.23	1	LUF/C-15	3	LUKE

32.50	115.40	1	NJK-45	4	EL CENTRO
32.39	114.36	1	NYL-46	5	YUMA
35.41	117.41	1	NID-47	6	CHINA LAKE
34.17	116.10	1	NXP-48	7	29 PALMS
34.51	116.47	1	DAG-49	8	DAGGETT
34.12	119.12	1	OXR-50	9	OXNARD
34.54	117.52	1	EDW-52	10	EDWARDS
34.43	120.34	2	VBG-51	11,12	VANDENBERG
32.09	110.52	1	DMA-75	13	DAVIS-MONTHAN

NZY output file:

ARCS IN THE SOLUTION

13 3
6 2
3 2
10 6
11 9
13 5
10 8
8 7
9 4
4 1
5 1
7 1
11 1

12 1 TWICE

THE TOTAL COST=
4546

Cost explanation:
-Run made over 2 week period
-15 arcs in solution

Weekly milage:

$\frac{4546 - (15 \times 150)}{2} = 1148$

OFF data file (11 depot):

Frequency based on every other month due
to infrequent service at YWG.

41.07	95.54	1	OFF/C-7	1	OFFUTT
37.37	97.16	8	IAB/C-22	2-9	MCCONNELL
38.32	89.51	8	BLV/C-23	10-17	SCOTT
43.34	96.44	4	FSD-86	18-21	SIOUX FALLS
42.24	96.23	4	SUX-87	22-25	SIOUX CITY
39.22	94.54	4	FLV-88	26-29	FT LEAVENWORTH
39.03	96.46	4	FRI-89	30-33	FT RILEY
38.51	94.33	4	GVW-90	34-37	KANSAS CITY
38.57	95.39	4	FOE-91	38-41	FORBES
37.44	92.08	4	TBN-92	42-45	FORNEY
38.44	93.33	8	SZL-94	46-53	WHITEMAN
38.34	90.09	16	CPS-95	54-69	E ST LOUIS
48.24	101.21	8	MIB-55	70-77	MINOT
47.57	97.24	8	RDR-56	78-85	GRAND FORKS
49.54	97.14	1	YWG-61	86	WINNEPEG
39.46	104.53	8	DEN/C-6	87-94	DENVER
41.09	104.49	8	CYS-53	95-102	CHEYENNE

44.08	103.06	8	RCA-54	103-110	ELLSWORTH
45.48	108.32	4	BIL-59	111-114	BILLINGS

OFF output file:

ARCS IN THE SOLUTION

86 70
86 78
111 71
112 72
113 73
114 74
79 71
80 72
81 73
82 74
83 75
84 76
85 77
95 87
96 88
97 89
98 90
99 91
100 92
101 93
102 94
111103
112104
113105
114106
54 10
55 11
56 12
57 13
58 14
59 15
60 16
61 17
107 70
108 75
109 76
110 77
42 10
43 11
44 12
45 13
46 42
47 43
48 44
49 45
58 50
59 51

60 52
61 53
78 18
83 19
84 20
85 21
46 34
47 35
48 36
49 37
30 2
31 3
32 4
33 5
87 2
88 3
89 4
90 5
91 6
92 7
93 8
94 9
38 6
39 7
40 8
41 9
34 26
35 27
36 28
37 29
22 18
23 19
24 20
25 21
14 1
15 1
16 1
17 1
22 1
23 1
24 1
25 1
26 1
27 1
28 1
29 1
30 1
31 1
32 1
33 1
38 1
39 1
40 1

41 1
 50 1
 51 1
 52 1
 53 1
 54 1
 55 1
 56 1
 57 1
 62 1 TWICE
 63 1 TWICE
 64 1 TWICE
 65 1 TWICE
 66 1 TWICE
 67 1 TWICE
 68 1 TWICE
 69 1 TWICE
 79 1
 80 1
 81 1
 82 1
 95 1
 96 1
 97 1
 98 1
 99 1
 100 1
 101 1
 102 1
 103 1
 104 1
 105 1
 106 1
 107 1
 108 1
 109 1
 110 1

THE TOTAL COST=
 56556

Cost explanation:

-Run made over 8 weeks
 -145 arcs in solution

Weekly milage=

$$\frac{56556 - (145 * 150)}{8} = 4351$$

 FFO data file (11 depot):

39.50	84.03	1	FFO/C-8	1	WRIGHT-PATT
42.05	87.49	1	NBU/C-24	2	GLENVIEW
38.10	85.44	2	SDF/C-25	3,4	STANDIFORD
41.32	93.39	1	DSM-81	5	DES MOINES
41.53	91.42	1	CID-82	6	CEDAR RAPIDS
41.26	90.30	1	MLI-83	7	MOLINE
43.57	90.44	1	CMY-84	8	FT MCCOY
44.53	93.13	1	MSP-85	9	MINNEAPOLIS
42.57	87.53	1	MKE-96	10	MILWAUKEE
42.18	85.14	1	BTL-97	11	BATTLE CREEK

41.35	83.48	1	TOL-98	12	TOLEDO
41.01	83.41	1	FDY-99	13	FINDLAY
41.25	81.51	1	CLE-100	14	CLEVELAND
40.29	80.14	1	PIT-101	15	PITTSBURGH
39.49	82.56	1	LCK-102	16	COLUMBUS
40.49	82.30	1	MFD-103	17	MANSFIELD
40.58	85.11	1	FWA-104	18	FORT WAYNE
40.38	86.09	1	GUS-105	19	GRISSOM
39.27	87.18	1	HUF-106	20	TERRE HAUTE
40.29	88.55	1	BMI-107	21	BLOOMINGTON IL
39.09	86.37	1	BMG-108	22	BLOOMINGTON IN
39.06	84.25	1	LUK-109	23	CINCINATI
39.38	79.54	2	MGW-142	24,25	MORGANTOWN

FFO output file:

ARCS IN THE SOLUTION

9 8
 9 5
 6 5
 7 6
 10 8
 21 7
 24 15
 11 2
 22 20
 15 14
 19 2
 12 11
 17 14
 22 3
 20 19
 13 12
 23 3
 18 13
 24 4
 25 16
 4 1
 10 1
 16 1
 17 1
 18 1
 21 1
 23 1
 25 1

THE TOTAL COST=
7529

Cost explanation:

-Run made over 2 weeks
-28 arcs in solution

Weekly milage =

$$\frac{7529 - (28 * 150)}{2} = 1665$$

LRF data file (11 depot):

Frequency based on 2 week rate.

34.54	92.08	1	LRF/C-20	1	LITTLE ROCK
35.02	89.58	1	MEM/C-21	2	MEMPHIS
32.30	93.40	2	BAD-63	3,4	BARKSDALE
31.19	92.32	1	AEX-70	5	ENGLAND
35.20	94.22	1	FSM-71	6	FT SMITH
34.29	93.06	1	HOT-72	7	HOT SPRINGS
35.58	89.57	2	BYH-93	8,9	BLYTHEVILLE

LRF output file:

ARCS IN THE SOLUTION

5 3
8 2
6 3
7 4
5 2
9 4
6 1
7 1
8 1
9 1

Cost explanation:

-run made over 2 weeks
-10 arcs in solution

Weekly cost=

$\frac{3099 - (10 \times 15)}{2} = 800$

THE TOTAL COST=
3099

NIP data file (11 depot):

Frequency based on 2 week rate.

30.14	81.41	1	NIP/C-12	1	JACKSONVILLE
29.50	90.01	1	NBG/C-27	2	NEW ORLEANS
27.50	82.31	2	MCF/C-28	3,4	MACDILL
25.29	80.23	2	HST/C-29	5,6	HOMESTEAD
33.54	84.31	2	NCQ/C-30	7,8	DOBBINS
32.19	90.05	1	JAN-69	9	JACKSON
36.40	87.29	1	HOP-110	10	FT CAMPBELL
35.24	86.05	1	TUH-111	11	TULLAHOMA
34.40	86.41	4	HUA-137	12-15	HUNTSVILLE
33.39	88.27	2	CBM-150	16,17	COLUMBUS
33.33	86.45	2	BHM-151	18,19	BIRMINGHAM
33.35	85.51	2	ANB-152	20,21	ANNISTON
32.38	83.35	2	WRB-155	22,23	ROBINS
32.20	84.59	2	LSF-156	24,25	LAWSON
32.22	86.21	2	MXF-157	26,27	MAXWELL
32.20	88.44	2	MEI-158	28,29	MERIDIAN
31.16	85.42	2	OZR-159	30,31	FT RUCKER
31.32	84.12	2	ABY-160	32,33	ALBANY
24.35	81.41	2	NOX-161	34,35	KEY WEST
26.41	80.06	2	PBI-162	36,37	PALM BEACH
28.14	80.36	2	COF-163	38,39	PATRICK
28.25	81.19	2	MCO-164	40,41	ORLANDO
30.24	88.55	2	BIX-165	42,43	KEESLER
30.21	87.19	2	NPA-166	44,45	PENSACOLA

30.29	86.31	2	VPS-167	46,47	EGLIN
30.04	85.34	2	PAM-168	48,49	TYNDALL
30.58	83.11	1	VAD-169	50	MOODY
30.23	84.21	1	TLH-170	51	TALLAHASSEE

NIP output file:

ARCS IN THE SOLUTION

28	9
11	10
42	9
16	9
12	10
29	17
16	12
17	13
29	2
18	13
19	14
44	42
45	43
20	14
21	15
26	19
15	7
46	43
27	21
20	8
36	5
37	6
45	27
30	26
47	30
48	47
31	24
22	8
49	31
24	23
32	25
51	49
38	36
39	37
5	3
6	4
33	23
40	38
41	39
50	32
25	3
4	1
7	1
11	1
18	1

22 1
 28 1
 33 1
 34 1 TWICE
 35 1 TWICE
 40 1
 41 1
 44 1
 46 1
 48 1
 50 1
 51 1
 THE TOTAL COST=
 16100

Cost explanation:
 -Run over 2 week period
 -59 arcs in solution

Weekly milage=

$$\frac{16100 - (59 * 150)}{2} = 3625$$

NZW data file (11 depots):

Frequency based on weekly rate.

42.09	70.56	1	NZW/C-9	1	BOSTON
41.35	71.25	1	OQW-114	2	QUONSET STATE
41.04	73.42	1	HPN-115	3	WHITE PLAINS
42.45	73.48	1	ALB-118	4	ALBANY
42.11	72.31	1	CEF-119	5	WESTOVER
40.44	73.25	1	FRG-120	6	FARMINGTON
41.30	74.06	1	SWF-121	7	STEWART
41.16	72.53	1	HVN-125	8	NEW HAVEN
41.19	72.02	1	GON-126	9	GROTON
41.56	72.41	1	BDL-127	10	BRADLEY
42.56	71.26	1	MHT-130	11	MANCHESTER
43.04	70.49	1	PSM-131	12	PEASE
43.53	69.56	1	NHZ-132	13	BRUNSWICK
44.48	68.50	1	BGR-133	14	BANGOR
46.57	67.53	1	LIZ-134	15	LORING
41.40	70.31	1	FMH-135	16	OTIS

NZW output file:

ARCS IN THE SOLUTION

15 14
 6 3
 7 3
 15 13
 7 4
 8 6
 10 4
 9 8
 10 5
 13 12
 9 2
 12 11
 16 2

5	1		Cost explanation:
11	1		-Runs made over 1 week
14	1		-17 arcs in solution
16	1		
THE TOTAL COST=		Weekly milage =	
3852		3852-(17*150) =	1302

RME data file (11 depot):

Frequency based on weekly rate.

43.14	75.24	1	RME/C-26	1	GRIFFIS
43.07	76.06	1	SYR-116	2	SYRACUSE
44.03	75.44	1	GTB-117	3	WHEELER SACK
42.12	75.59	1	BGM-122	4	BINGHAMTON
42.56	78.44	1	BUF-123	5	BUFFALO
43.07	77.40	1	ROC-124	6	ROCHESTER
44.39	73.28	1	PBG-128	7	PLATTSBURGH
44.28	73.09	1	BTB-129	8	BURLINGTON
41.20	75.43	1	AVP-145	9	WILKES-BARRE

RME output file:

ARCS IN THE SOLUTION

8	7		
6	5		
9	4	Cost explanation:	
9	5	-Runs made over one week	
7	3	-9 arcs in solution	
6	3		
4	2	Weekly milage=	
2	1	2149-(9*150) =	799
8	1		
THE TOTAL COST=			
2149			

11 Depot summary:

Depot	Weekly Milage		
SKF	1751		
CHS	487		
BWI	3638		
SUU	4504		
NZY	1148		
OFF	4351		
FFO	1665		
LRF	800		
NIP	3625		
NZW	1302		
RME	799	TOTAL =	24070
		YEARLY TOTAL	1,251,640

10 Depot Model

MSF:

BEST WEIGHT= 294024

DEPOTS=

1	2	3	7	8	9	11	12	20	26
EMINATING NODES ON TOP									
INCIDENT NODES BELOW									
26	9	1	1	9	114	126	125	115	115
116	135	31	34	114	126	125	115	120	121
125	127	11	8	34	32	35	26	8	9
127	119	153	109	32	35	33	117	102	130
130	20	116	122	3	153	3	143	131	102
131	72	122	145	139	154	143	146	132	103
103	103	99	139	176	136	146	176	138	119
100	99	98	176	136	10	144	138	140	118
11	2	67	99	104	116	124	132	11	32
148	67	66	104	105	124	123	133	147	36
140	141	180	181	181	177	172	180	179	173
141	180	181	178	177	172	171	179	173	174
174	174	98	72	7	87	109	25	108	153
175	112	97	71	87	86	25	108	106	149
12	169	160	156	160	170	168	167	167	157
169	160	156	157	170	168	167	166	159	151
151	151	137	152	160	166	165	151	150	158
152	137	111	30	155	165	27	150	158	69
31	38	100	101	106	107	83	82	141	33*
38	39	101	142	107	83	82	81	113	52*
52	50	51	51	49	48	45	45	111	66
50	51	47	49	48	45	46	5	110	18
18	78	62	62	117	128	20	21	107	24
78	62	68	19	128	129	21	93	24	96
12	164	164	163	162	29	7	88	88	90
164	163	28	162	29	161	88	90	91	94
91	89	94	92	95	2	78	65	49	72
89	22	92	95	23	77	65	64	14	63
63	46	15	68	80	76	82	84	133	67
70	15	75	80	76	79	84	85	134	73

76	16	74	38	39	44	44	58	58	60
16	74	17	37	44	43	58	13	60	57
43	42	40	42	86	56	56	55	54	53
42	40	4	41	56	61	55	54	53	6
54									
59									

* Note the asterisked entry; it is the only link that is different from the 11 depot model. The consequence is the joining of the NZY tree to the SUU tree.

New SUU CW.

Data file:

Frequency based on 2 week rate.

38.15	121.55	1	SUU/F-1	1	TRAVIS
38.40	121.23	2	MCC-31	2,3	MCCLELLAN
37.17	120.31	2	MCE-32	4,5	MERCED
36.20	119.57	2	NLC-33	6,7	LEMOORE
37.53	121.14	2	SCK-34	8,9	STOCKTON
36.46	119.43	2	FAT-35	10,11	FRESNO
36.35	121.50	2	MRY-36	12,13	MONTERRY
42.09	121.44	1	LMT-37	14	KLAMATH FALLS
39.29	119.46	1	RNO-38	15	RENO
39.24	118.41	1	NFL-39	16	FALLON
40.47	111.58	2	SLC/C-13	17,18	SALT LAKE CITY
47.08	122.28	2	TCM/C-4	19,20	MCCHORD
46.34	120.32	2	YKM-40	21,22	YAKIMA
47.37	117.31	2	GEG-41	23,24	SPOKANE
46.15	119.06	1	PSC-42	25	PASCO
43.33	116.13	1	BOI-43	26	BOISE
43.02	115.52	1	MUO-44	27	MT HOME
47.30	111.11	2	GFA-57	28,29	MALMSTROM
43.31	112.04	1	IDA-58	30	IDAHO FALLS
46.36	111.59	1	HLN-60	31	HELENA
32.41	117.12	2	NZY/C-5	32,33	NORTH ISLAND
36.14	115.02	1	LSV/C-14	34	LAS VEGAS
33.32	112.23	1	LUF/C-15	35	LUKE
32.50	115.40	1	NJK-45	36	EL CENTRO
32.39	114.36	1	NYL-46	37	YUMA
35.41	117.41	1	NID-47	38	CHINA LAKE
34.17	116.10	1	NXP-48	39	29 PALMS
34.51	116.47	1	DAG-49	40	DAGGETT
34.12	119.12	1	OXR-50	41	OXNARD
34.54	117.52	1	EDW-52	42	EDWARDS
34.43	120.34	2	VBG-51	43,44	VANDENBERG
32.09	110.52	1	DMA-75	45	DAVIS-MONTHAN

New SUU output file:

ARCS IN THE SOLUTION

31	28
45	35
28	23
29	24
30	29
25	23
45	37
21	19
22	20
37	36
27	26
36	32
39	33
27	17
40	39
40	34
42	33
42	38
21	18
20	14
43	41
17	16
44	38
41	6
10	6
11	7
26	15
43	12
10	4
11	5
13	7
8	4
9	5
15	2
22	3
2	1
3	1
8	1
9	1
12	1
13	1
14	1
16	1
18	1
19	1
24	1
25	1
30	1
31	1

32	1	Cost explanation:
34	1	-Runs over 2 weeks
35	1	-53 arcs in solution
44	1	
THE TOTAL COST=		Weekly milage=
20187		$\frac{20187 - (53 \times 150)}{2} = 6119$

10 Depot summary:

11 depot weekly miles	24070	
minus old SUU and NZY	-4504	
	-1148	
plus new SUU	<u>+6119</u>	Yearly milage:
new weekly milage	24537	1,275,924

9 Depot Model

MSF:

BEST WEIGHT= 309987

DEPOTS=

1 2 3 7 8 9 11 12 26

EMINATING NODES ON TOP

INCIDENT NODES BELOW

26	9	1	1	9	114	126	125	115	115
116	135	31	34	114	126	125	115	120	121
125	127	11	8	34	32	35	26	8	9
127	119	153	109	32	35	33	117	102	130
130	116	122	3	153	3	143	131	102	103
131	122	145	139	154	143	146	132	103	100
103	99	139	176	136	146	176	138	119	11
99	98	176	136	10	144	138	140	118	148
2	67	99	104	116	124	132	11	32	140
67	66	104	105	124	123	133	147	36	141
141	180	181	181	177	172	180	179	173	174
180	181	178	177	172	171	179	173	174	175
174	98	7	87	109	25	108	153	12	169
112	97	87	86	25	108	106	149	169	160
160	156	160	170	168	167	167	157	151	151
156	157	170	168	167	166	159	151	152	137
137	152	160	166	165	151	150	158	31	38
111	30	155	165	27	150	158	69	38	39
100	101	106	107	83	82	141	33	52	50
101	142	107	83	82	81	113	52	50	51
51	51	49	48	45	45	111	66	18	78
47	49	48	45	46	5	110	18	78	62
62	62	117	128	107	24	12	164	164	163
68	19	128	129	24	96	164	163	28	162
162	29	150*	21	21	20	72	7	88	88
29	161	21*	93	20	72	71	88	90	91
90	91	89	94	92	95	2	78	65	49
94	89	22	92	95	23	77	65	64	14
72	63	46	15	68	80	76	82	84	133
63	70	15	75	80	76	79	84	85	134

67	76	16	74	38	39	44	44	58	58
73	16	74	17	37	44	43	58	13	60
60	43	42	40	42	86	56	56	55	54
57	42	40	4	41	56	61	55	54	53
53	54								
6	59								

* Asterisk indicates the link which combines LRF stations into NIP. The only new route structure which requires CW computation is NIP.

New NIP CW:

Data file:

Frequency based on 2 week rate.

30.14	81.41	1	NIP/C-12	1	JACKSONVILLE
29.50	90.01	1	NBG/C-27	2	NEW ORLEANS
27.50	82.31	2	MCF/C-28	3,4	MACDILL
25.29	80.23	2	HST/C-29	5,6	HOMESTEAD
33.54	84.31	2	NCQ/C-30	7,8	DOBBINS
32.19	90.05	1	JAN-69	9	JACKSON
36.40	87.29	1	HOP-110	10	FT CAMPBELL
35.24	86.05	1	TUH-111	11	TULLAHOMA
34.40	86.41	4	HUA-137	12-15	HUNTSVILLE
33.39	88.27	2	CBM-150	16,17	COLUMBUS
33.33	86.45	2	BHM-151	18,19	BIRMINGHAM
33.35	85.51	2	ANB-152	20,21	ANNISTON
32.38	83.35	2	WRB-155	22,23	ROBINS
32.20	84.59	2	LSF-156	24,25	LAWSON
32.22	86.21	2	MXF-157	26,27	MAXWELL
32.20	88.44	2	MEI-158	28,29	MERIDIAN
31.16	85.42	2	OZR-159	30,31	FT RUCKER
31.32	84.12	2	ABY-160	32,33	ALBANY
24.35	81.41	2	NOX-161	34,35	KEY WEST
26.41	80.06	2	PBI-162	36,37	PALM BEACH
28.14	80.36	2	COF-163	38,39	PATRICK
28.25	81.19	2	MCO-164	40,41	ORLANDO
30.24	88.55	2	BIX-165	42,43	KEESLER
30.21	87.19	2	NPA-166	44,45	PENSACOLA
30.29	86.31	2	VPS-167	46,47	EGLIN
30.04	85.34	2	PAM-168	48,49	TYNDALL
30.58	83.11	1	VAD-169	50	MOODY
30.23	84.21	1	TLH-170	51	TALLAHASSEE
34.54	92.08	1	LRF/C-20	52	LITTLE ROCK
35.02	89.58	1	MEM/C-21	53	MEMPHIS
32.30	93.40	2	BAD-63	54,55	BARKSDALE
31.19	92.32	1	AEX-70	56	ENGLAND
35.20	94.22	1	FSM-71	57	FT SMITH

34.29	93.06	1	HOT-72	58	HOT SPRINGS
35.58	89.57	2	BYH-93	59,60	BLYTHEVILLE

New NIP output file:

ARCS IN THE SOLUTION

58	57
57	52
58	54
56	55
59	53
55	53
60	10
60	16
28	9
11	10
42	2
16	9
29	17
17	12
29	2
18	12
19	13
44	42
45	43
20	13
21	14
26	19
14	7
15	8
46	43
27	15
36	5
37	6
45	26
24	21
30	27
47	30
48	47
25	8
31	24
22	7
49	31
25	23
51	49
38	36
39	37
5	3
6	4
32	22
40	38
41	39
50	33

33 3
 4 1
 11 1
 18 1
 20 1
 23 1
 28 1
 32 1
 34 1 TWICE
 35 1 TWICE
 40 1
 41 1
 44 1
 46 1
 48 1
 50 1
 51 1
 52 1
 54 1
 56 1
 59 1

Cost explanation:
 -Runs over 2 weeks
 -70 arcs in solution

Weekly milage =

$$\frac{21521 - (70 * 150)}{2} = 5510$$

THE TOTAL COST=
 21521

 9 Depot Summary:

10 depot weekly miles	24537	
minus old NIP and LRF	-3625	
	- 800	
plus new NIP	<u>+5510</u>	Yearly milage
new weekly milage	25622	1,332,344

8 Depot Model

MSF:

BEST WEIGHT= 332287

DEPOTS=

1 2 3 7 8 9 12 26

EMINATING NODES ON TOP

INCIDENT NODES BELOW

26	9	1	1	9	114	126	125	115	115
116	135	31	34	114	126	125	115	120	121
125	127	8	34	32	35	26	8	9	130
127	119	109	32	35	33	117	102	130	131
116	122	3	3	143	131	102	103	103	99
122	145	139	143	146	132	103	100	99	98
139	176	136	146	176	138	119	2	67	99
176	136	10	144	138	140	118	67	66	104
104	116	124	132	32	140	141	180	181	181
105	124	123	133	36	141	180	181	178	177
177	172	180	179	173	174	174	98	179*	148
172	171	179	173	174	175	112	97	148*	11
11	153	11	7	87	109	25	108	148	12
153	154	147	87	86	25	108	106	149	169
169	160	156	160	170	168	167	167	157	151
160	156	157	170	168	167	166	159	151	152
151	137	152	160	166	165	151	150	158	31
137	111	30	155	165	27	150	158	69	38
38	100	101	106	107	83	82	141	33	52
39	101	142	107	83	82	81	113	52	50
50	51	51	49	48	45	45	111	66	18
51	47	49	48	45	46	5	110	18	78
78	62	62	117	128	107	24	12	164	164
62	68	19	128	129	24	96	164	163	28
163	162	29	150	21	21	20	72	7	88
162	29	161	21	93	20	72	71	88	90
88	90	91	89	94	92	95	2	78	65
91	94	89	22	92	95	23	77	65	64
49	72	63	46	15	68	80	76	82	84
14	63	70	15	75	80	76	79	84	85

133	67	76	16	74	38	39	44	44	58
134	73	16	74	17	37	44	43	58	13
58	60	43	42	40	42	86	56	56	55
60	57	42	40	4	41	56	61	55	54
54	53	54							
53	6	59							

*Asterisk denotes new link from 9 depot MSF. This link combines CHS into BWI; BWI routes require altering.

New BWI CW:

Data file:

Frequency based on 2 week rate.

39.11	76.40	1	BWI/F-3	1	BALTIMORE
36.56	76.17	2	NGU/C-10	2,3	NORFOLK
35.49	84.00	1	TYS-112	4	KNOXVILLE
38.22	81.36	1	CUW-113	5	CHARLESTON WV
37.05	76.21	12	LFI-136	6-17	LANGLEY
38.08	78.27	2	CHO-138	18,19	CHARLOTTESVILLE
38.17	76.24	2	NHK-139	20,21	PAX RIVER
38.15	78.53	2	SHD-140	22,23	SHENENDOAH
37.19	79.58	2	ROA-141	24,25	ROANOKE
39.42	77.43	2	HGR-143	26,27	HAGERSTOWN
40.51	77.51	2	UNV-144	28,29	STATE COLLEGE
40.11	76.45	2	MDT-146	30,31	HARRISBURG
34.54	76.53	2	NKT-171	32,33	CHERRY POINT
34.43	77.26	2	NCA-172	34,35	JACKSONVILLE
34.54	82.13	2	GSP-173	36,37	GREENSVILLE
35.26	82.32	2	AVL-174	38,39	ASHEVILLE
36.29	82.25	2	TRI-175	40,41	BRISTOL
37.31	77.19	2	RIC-176	42,43	RICHMOND
35.20	77.58	2	GSB-177	44,45	GOLDSBORO
35.10	79.01	2	POB-178	46,47	POPE
35.13	80.56	2	CLT-179	48,49	CHARLOTTE
36.06	79.56	2	GSO-180	50,51	GREENSBORO
35.53	78.47	2	RDU-181	52,53	RALIEGH
32.53	80.02	2	CHS/C-11	54,55	CHARLESTON
33.40	78.55	2	MYR-147	56,57	MYRTLE BEACH
33.57	80.28	2	SSC-148	58,59	SHAW
33.22	81.58	2	AGS-149	60,61	FT GORDON
32.28	80.43	2	NBC-153	62,63	BEAUFORT
31.53	81.34	2	LHW-154	64,65	FT STEWART

New BWI output file:

ARCS IN THE SOLUTION
64 62

65	63	
64	60	
65	61	
62	54	
63	55	
60	58	
61	5 ^a	
38	36	
39	37	
38	4	
56	54	
57	55	
40	4	
48	36	
49	37	
41	39	
58	46	
59	47	
56	34	
57	35	
50	48	
51	49	
44	32	
45	33	
40	5	
52	44	
53	45	
52	51	
50	24	
53	25	
33	2	
6	2	
7	3	
24	22	
25	23	
23	18	
42	3	
43	6	
42	19	
20	7	
21	8	
30	28	
31	29	
28	26	
29	27	
26	19	
27	8	
5	1	
9	1	TWICE
10	1	TWICE
11	1	TWICE
12	1	TWICE
13	1	TWICE

14 1 TWICE
 15 1 TWICE
 16 1 TWICE
 17 1 TWICE
 18 1
 20 1
 21 1
 22 1
 30 1
 31 1
 32 1
 34 1
 35 1
 41 1
 43 1
 46 1
 47 1

Cost explanation:
 -Runs made over 2 weeks
 -80 arcs in solution

Weekly cost =

$$\frac{21330 - (80 \times 150)}{2} = 4665$$

THE TOTAL COST=
 21330

 8 Depot summary

9 depot weekly milage	25622	
minus old CHS and BWI	- 487	
	-3638	
plus new BWI	<u>+4665</u>	Yearly milage:
new weekly milage	26162	1,360,424

7 Depot Model

MSF:

BEST WEIGHT= 358419

DEPOTS=

1 2 3 7 8 9 12

EMINATING NODES ON TOP

INCIDENT NODES BELOW

9	1	1	9	114	126	125	115	115	125
135	31	34	114	126	125	115	120	121	127
127	8	34	32	35	8	9	130	3	3
119	109	32	35	33	102	130	131	139	143
143	131	102	103	103	99	139	176	136	146
146	132	103	100	99	98	176	136	10	144
176	138	119	2	67	99	104	132	121*	145
138	140	118	67	66	104	105	133	145*	122
122	116	26	116	124	32	140	141	180	181
116	26	117	124	123	36	141	180	181	178
181	177	172	180	179	173	174	174	98	179
177	172	171	179	173	174	175	112	97	148
148	11	153	11	7	87	109	25	108	148
11	153	154	147	87	86	25	108	106	149
12	169	160	156	160	170	168	167	167	157
169	160	156	157	170	168	167	166	159	151
151	151	137	152	160	166	165	151	150	158
152	137	111	30	155	165	27	150	158	69
31	38	100	101	106	107	83	82	141	33
38	39	101	142	107	83	82	81	113	52
52	50	51	51	49	48	45	45	111	66
50	51	47	49	48	45	46	5	110	18
18	78	62	62	117	128	107	24	12	164
78	62	68	19	128	129	24	96	164	163
164	163	162	29	150	21	21	20	72	7
28	162	29	161	21	93	20	72	71	88
88	88	90	91	89	94	92	95	2	78
90	91	94	89	22	92	95	23	77	65
65	49	72	63	46	15	68	80	76	82
64	14	63	70	15	75	80	76	79	84

84	133	67	76	16	74	38	39	44	44
85	134	73	16	74	17	37	44	43	58
58	58	60	43	42	40	42	86	56	56
13	60	57	42	40	4	41	56	61	55
55	54	53	54						
54	53	6	59						

* New link joins RME locations into NZW route system.
New NZW route system required.

New NZW CW:

Data set:

Frequency based on weekly rate.

42.09	70.56	1	NZW/C-9	1	SOUTH WEYMOUTH
41.35	71.25	1	OQW-114	2	QUONSET STATE
41.04	73.42	1	HPN-115	3	WHITE PLAINS
42.45	73.48	1	ALB-118	4	ALBANY
42.11	72.31	1	CEF-119	5	WESTOVER
40.44	73.25	1	FRG-120	6	FARMINGTON
41.30	74.06	1	SWF-121	7	STEWART
41.16	72.53	1	HVN-125	8	NEW HAVEN
41.19	72.02	1	GON-126	9	GROTON
41.56	72.41	1	BDL-127	10	BRADLEY
42.56	71.26	1	MHT-130	11	MANCHESTER
43.04	70.49	1	PSM-131	12	PEASE
43.53	69.56	1	NHZ-132	13	BRUNSWICK
44.48	68.50	1	BGR-133	14	BANGOR
46.57	67.53	1	LIZ-134	15	LORING
41.40	70.31	1	FMH-135	16	OTIS
43.14	75.24	1	RME/C-26	17	GRIFFIS
43.07	76.06	1	SYR-116	18	SYRACUSE
44.03	75.44	1	GTB-117	19	WHEELER SACK
42.12	75.59	1	BGM-122	20	BINGHAMTON
42.56	78.44	1	BUF-123	21	BUFFALO
43.07	77.40	1	ROC-124	22	ROCHESTER
44.39	73.28	1	PBG-128	23	PLATTSBURGH
44.28	73.09	1	BTB-129	24	BURLINGTON
41.20	75.43	1	AVP-145	25	WILKES-BARRE

New NZW output file:

ARCS IN THE SOLUTION

22 21
21 18
22 19
18 17
25 20

15 14
 20 17
 24 23
 23 19
 6 3
 7 3
 15 13
 7 4
 8 6
 10 4
 9 8
 10 5
 13 12
 9 2
 12 11
 16 2
 5 1
 11 1
 14 1
 16 1
 24 1
 25 1

THE TOTAL COST=
 6415

Cost explanation:
 -Runs made over 1 week
 -27 arcs in solution

Weekly milage =
 $6415 - (27 * 150) = 2365$

 7 Depot summary

8 depot weekly milage	26162	
minus old RME and NZW	- 799	
	-1302	
plus new NZW	<u>+2365</u>	Yearly milage:
new weekly milage	26426	1,374,152

6 Depot Model

MSF:

BEST WEIGHT= 387217
DEPOTS=

1	2	3	7	8	12					
EMINATING NODES ON TOP										
INCIDENT NODES BELOW										
1	1	8	34	32	35	8	3	3	143	
31	34	109	32	35	33	102	139	143	146	
102	103	103	99	139	176	136	146	176	138	
103	100	99	98	176	136	10	144	138	140	
2	67	99	104	32	140	141	180	181	181	
67	66	104	105	36	141	180	181	178	177	
177	172	180	179	173	174	174	98	179	148	
172	171	179	173	174	175	112	97	148	11	
11	153	11	7	87	109	25	108	148	146*	
153	154	147	87	86	25	108	106	149	145*	
145	122	116	26	116	124	145	121	115	115	
122	116	26	117	124	123	121	115	120	125	
125	126	114	9	125	127	9	130	131	119	
126	114	9	135	127	119	130	131	132	118	
132	12	169	160	156	160	170	168	167	167	
133	169	160	156	157	170	168	167	166	159	
157	151	151	137	152	160	166	165	151	150	
151	152	137	111	30	155	165	27	150	158	
158	31	38	100	101	106	107	83	82	141	
69	38	39	101	142	107	83	82	81	113	
33	52	50	51	51	49	48	45	45	111	
52	50	51	47	49	48	45	46	5	110	
66	18	78	62	62	117	128	107	24	12	
18	78	62	68	19	128	129	24	96	164	
164	164	163	162	29	150	21	21	20	72	
163	28	162	29	161	21	93	20	72	71	
7	88	88	90	91	89	94	92	95	2	
88	90	91	94	89	22	92	95	23	77	
78	65	49	72	63	46	15	68	80	76	
65	64	14	63	70	15	75	80	76	79	

82	84	133	67	76	16	74	38	39	44
84	85	134	73	16	74	17	37	44	43
44	58	58	60	43	42	40	42	86	56
58	13	60	57	42	40	4	41	56	61
56	55	54	53	54					
55	54	53	6	59					

*New link from 7 depot MSF. Depot at NZW is eliminated;
depot at BWI enlarges.

New BWI CW:

Data set.

Frequency based on 2 week rate.

39.11	76.40	1	BWI/F-3	1	BALTIMORE
36.56	76.17	2	NGU/C-10	2,3	NORFOLK
35.49	84.00	1	TYS-112	4	KNOXVILLE
38.22	81.36	1	CUW-113	5	CHARLESTON WV
37.05	76.21	12	LFI-136	6-17	LANGLEY
38.08	78.27	2	CHO-138	18,19	CHARLOTTESVILLE
38.17	76.24	2	NHK-139	20,21	PAX RIVER
38.15	78.53	2	SHD-140	22,23	SHENENDOAH
37.19	79.58	2	ROA-141	24,25	ROANOKE
39.42	77.43	2	HGR-143	26,27	HAGERSTOWN
40.51	77.51	2	UNV-144	28,29	STATE COLLEGE
40.11	76.45	2	MDT-146	30,31	HARRISBURG
34.54	76.53	2	NKT-171	32,33	CHERRY POINT
34.43	77.26	2	NCA-172	34,35	JACKSONVILLE
34.54	82.13	2	GSP-173	36,37	GREENSVILLE
35.26	82.32	2	AVL-174	38,39	ASHEVILLE
36.29	82.25	2	TRI-175	40,41	BRISTOL
37.31	77.19	2	RIC-176	42,43	RICHMOND
35.20	77.58	2	GSB-177	44,45	GOLDSBORO
35.10	79.01	2	POB-178	46,47	POPE
35.13	80.56	2	CLT-179	48,49	CHARLOTTE
36.06	79.56	2	GSO-180	50,51	GREENSBORO
35.53	78.47	2	RDU-181	52,53	RALIEGH
32.53	80.02	2	CHS/C-11	54,55	CHARLESTON
33.40	78.55	2	MYR-147	56,57	MYRTLE BEACH
33.57	80.28	2	SSC-148	58,59	SHAW
33.22	81.58	2	AGS-149	60,61	FT GORDON
32.28	80.43	2	NBC-153	62,63	BEAUFORT
31.53	81.34	2	LHW-154	64,65	FT STEWART
42.09	70.56	2	NZW/C-9	66,67	SOUTH WEYMOUTH
41.35	71.25	2	OQW-114	68,69	QUONSET STATE
41.04	73.42	2	HPN-115	70,71	WHITE PLAINS
42.45	73.48	2	ALB-118	72,73	ALBANY
42.11	72.31	2	CEF-119	74,75	WESTOVER

40.44	73.25	2	FRG-120	76,77	FARMINGTON
41.30	74.06	2	SWF-121	78,79	STEWART
41.16	72.53	2	HVN-125	80,81	NEW HAVEN
41.19	72.02	2	GON-126	82,83	GROTON
41.56	72.41	2	BDL-127	84,85	BRADLEY
42.56	71.26	2	MHT-130	86,87	MANCHESTER
43.04	70.49	2	PSM-131	88,89	PEASE
43.53	69.56	2	NHZ-132	90,91	BRUNSWICK
44.48	68.50	2	BGR-133	92,93	BANGOR
46.57	67.53	2	LIZ-134	94,95	LORING
41.40	70.31	2	FMH-135	96,97	OTIS
43.14	75.24	2	RME/C-26	98,99	GRIFFIS
43.07	76.06	2	SYR-116	100,101	SYRACUSE
44.03	75.44	2	GTB-117	102,103	WHEELER SACK
42.12	75.59	2	BGM-122	104,105	BINGHAMTON
42.56	78.44	2	BUF-123	106,107	BUFFALO
43.07	77.40	2	ROC-124	108,109	ROCHESTER
44.39	73.28	2	PBG-128	110,111	PLATTSBURGH
44.28	73.09	2	BTV-129	112,113	BURLINGTON
41.20	75.43	2	AVP-145	114,115	WILKES-BARRE

New BWI output file:

ARCS IN THE SOLUTION

94 92
 95 93
 64 62
 65 63
 64 60
 65 61
 92 90
 93 91
 62 54
 63 55
 60 58
 61 59
 90 88
 91 89
 38 36
 39 37
 112110
 113111
 112 94
 113 95
 38 4
 56 54
 57 55
 40 4
 48 36
 49 37
 41 39
 96 66

97 67
86 66
87 67
96 68
97 69
58 46
59 47
56 34
57 35
86 74
87 75
82 68
83 69
102 98
103 99
84 74
85 75
50 48
51 49
102100
103101
44 32
45 33
108106
109107
40 5
84 72
85 73
82 80
83 81
52 44
53 45
52 51
108 98
109 99
104100
105101
50 24
78 72
79 73
76 70
77 71
53 25
33 2
114104
115105
6 2
7 3
24 22
25 23
106 28
107 29
23 18

42 3
 43 6
 42 19
 114 30
 115 31
 20 7
 21 8
 28 26
 29 27
 76 8
 77 9
 5 1
 9 1
 10 1 TWICE
 11 1 TWICE
 12 1 TWICE
 13 1 TWICE
 14 1 TWICE
 15 1 TWICE
 16 1 TWICE
 17 1 TWICE
 18 1
 19 1
 20 1
 21 1
 22 1
 26 1
 27 1
 30 1
 31 1
 32 1
 34 1
 35 1
 41 1
 43 1
 46 1
 47 1
 70 1
 71 1
 78 1
 79 1
 80 1
 81 1
 88 1
 89 1
 110 1
 111 1
 THE TOTAL COST=
 36542

Cost explanation:
 -Run made over 2 weeks
 -136 arcs in solution

Weekly milage =

$$\frac{36542 - (136 * 150)}{2} = 8071$$

 6 Depot summary:

7 depot weekly milage	26426	
minus old NZW and BWI	-2365	
	-4665	
plus new BWI	<u>+8071</u>	Yearly milage:
6 depot weekly cost	27467	1,428,284

5 Depot Model

MSF:

BEST WEIGHT= 449824

DEPOTS=

1 2 3 7 12
EMINATING NODES ON TOP
INCIDENT NODES BELOW

1	1	34	32	35	3	3	143	139	176
31	34	32	35	33	139	143	146	176	136
136	146	176	138	2	67	32	140	141	180
10	144	138	140	67	66	36	141	180	181
181	181	177	172	180	179	173	174	174	179
178	177	172	171	179	173	174	175	112	148
148	11	153	11	7	87	148	146	145	122
11	153	154	147	87	86	149	145	122	116
116	26	116	124	145	121	115	115	125	126
26	117	124	123	121	115	120	125	126	114
114	9	125	127	9	130	131	119	132	12
9	135	127	119	130	131	132	118	133	169
169	160	156	160	170	168	167	167	157	151
160	156	157	170	168	167	166	159	151	152
151	137	152	160	166	165	151	150	158	31
137	111	30	155	165	27	150	158	69	38
38	140	142	101	100	103	99	103	102	8
39	142	101	100	103	99	98	102	8	109
99	104	98	109	25	108	106	107	83	141
104	105	97	25	108	106	107	83	82	113
33	52	50	51	51	49	48	45	45	111
52	50	51	47	49	48	45	46	5	110
66	18	78	62	62	117	128	7	107	24
18	78	62	68	19	128	129	81	24	96
12	164	164	163	162	29	150	21	21	20
164	163	28	162	29	161	21	93	20	72
72	7	88	88	90	91	89	94	92	95
71	88	90	91	94	89	22	92	95	23
2	78	65	49	72	63	46	15	68	80
77	65	64	14	63	70	15	75	80	76

76	82	133	67	76	16	74	86	38	39
79	84	134	73	16	74	17	85	37	44
44	44	58	58	60	43	42	40	42	85
43	58	13	60	57	42	40	4	41	56
56	56	55	54	53	54				
61	55	54	53	6	59				

Note, there are numerous changes due to splitting of FFO service locations to both OFF and BWI. New CW computations are required for OFF and BWI.

New BWI CW:

Data set:

Frequency based on 2 week rate.

39.11	76.40	1	BWI/F-3	1	BALTIMORE
36.56	76.17	2	NGU/C-10	2,3	NORFOLK
35.49	84.00	1	TYS-112	4	KNOXVILLE
38.22	81.36	1	CUW-113	5	CHARLESTON WV
37.05	76.21	12	LFI-136	6-17	LANGLEY
38.08	78.27	2	CHO-138	18,19	CHARLOTTESVILLE
38.17	76.24	2	NHK-139	20,21	PAX RIVER
38.15	78.53	2	SHD-140	22,23	SHENENDOAH
37.19	79.58	2	ROA-141	24,25	ROANOKE
39.42	77.43	2	HGR-143	26,27	HAGERSTOWN
40.51	77.51	2	UNV-144	28,29	STATE COLLEGE
40.11	76.45	2	MDT-146	30,31	HARRISBURG
34.54	76.53	2	NKT-171	32,33	CHERRY POINT
34.43	77.26	2	NCA-172	34,35	JACKSONVILLE
34.54	82.13	2	GSP-173	36,37	GREENSVILLE
35.26	82.32	2	AVL-174	38,39	ASHEVILLE
36.29	82.25	2	TRI-175	40,41	BRISTOL
37.31	77.19	2	RIC-176	42,43	RICHMOND
35.20	77.58	2	GSB-177	44,45	GOLDSBORO
35.10	79.01	2	POB-178	46,47	POPE
35.13	80.56	2	CLT-179	48,49	CHARLOTTE
36.06	79.56	2	GSO-180	50,51	GREENSBORO
35.53	78.47	2	RDU-181	52,53	RALIEGH
32.53	80.02	2	CHS/C-11	54,55	CHARLESTON
33.40	78.55	2	MYR-147	56,57	MYRTLE BEACH
33.57	80.28	2	SSC-148	58,59	SHAW
33.22	81.58	2	AGS-149	60,61	FT GORDON
32.28	80.43	2	NBC-153	62,63	BEAUFORT
31.53	81.34	2	LHW-154	64,65	FT STEWART
42.09	70.56	2	NZW/C-9	66,67	SOUTH WEYMOUTH
41.35	71.25	2	OQW-114	68,69	QUONSET STATE
41.04	73.42	2	FPN-115	70,71	WHITE PLAINS
42.45	73.48	2	ALB-118	72,73	ALBANY

42.11	72.31	2	CEF-119	74,75	WESTOVER
40.44	73.25	2	FRG-120	76,77	FARMINGTON
41.30	74.06	2	SWF-121	78,79	STEWART
41.16	72.53	2	HVN-125	80,81	NEW HAVEN
41.19	72.02	2	GON-126	82,83	GROTON
41.56	72.41	2	BDL-127	84,85	BRADLEY
42.56	71.26	2	MHT-130	86,87	MANCHESTER
43.04	70.49	2	PSM-131	88,89	PEASE
43.53	69.56	2	NHZ-132	90,91	BRUNSWICK
44.48	68.50	2	BGR-133	92,93	BANGOR
46.57	67.53	2	LIZ-134	94,95	LORING
41.40	70.31	2	FMH-135	96,97	OTIS
43.14	75.24	2	RME/C-26	98,99	GRIFFIS
43.07	76.06	2	SYR-116	100,101	SYRACUSE
44.03	75.44	2	GTB-117	102,103	WHEELER SACK
42.12	75.59	2	BGM-122	104,105	BINGHAMTON
42.56	78.44	2	BUF-123	106,107	BUFFALO
43.07	77.40	2	ROC-124	108,109	ROCHESTER
44.39	73.28	2	PBG-128	110,111	PLATTSBURGH
44.28	73.09	2	BTB-129	112,113	BURLINGTON
41.20	75.43	2	AVP-145	114,115	WILKES-BARRE
39.50	84.03	12	FFO/C-8	116-127	WRIGHT-PATT
42.05	87.49	1	NBU/C-24	128	GLENVIEW
38.10	85.44	2	SDF/C-25	129,130	STANDIFORD
41.53	91.42	1	CID-82	131	CEDAR RAPIDS
41.26	90.30	1	MLI-83	132	MOLINE
43.57	90.44	1	CMY-84	133	FT MCCOY
42.18	85.14	1	BTL-97	134	BATTLE CREEK
41.35	83.48	1	TOL-98	135	TOLEDO
41.01	83.41	1	FDY-99	136	FINDLAY
41.25	81.51	1	CLE-100	137	CLEVELAND
40.29	80.14	1	PIT-101	138	PITTSBURGH
39.49	82.56	1	LCK-102	139	COLUMBUS
40.49	82.30	1	MFD-103	140	MANSFIELD
40.58	85.11	1	FWA-104	141	FORT WAYNE
40.38	86.09	1	GUS-105	142	GRISSOM
39.27	87.18	1	HUF-106	143	TERRE HAUTE
40.29	88.55	1	BMI-107	144	BLOOMINGTON IL
39.09	86.37	1	BMG-108	145	BLOOMINGTON IN
39.06	84.25	1	LUK-109	146	CINCINATI
39.38	79.54	2	MGW-142	147,148	MORGANTOWN
42.57	87.53	1	MKE-96	149	MILWAUKEE

New BWI output file:

ARCS IN THE SOLUTION

132131
133131
144132
149128
94 92
95 93
145143

64 62
65 63
143128
149134
64 60
65 61
92 90
93 91
145129
62 54
63 55
142141
142130
60 58
61 59
146130
90 88
91 89
38 36
39 37
112110
113111
112 94
113 95
141135
38 4
56 54
57 55
136135
146116
40 4
48 36
49 37
41 39
96 66
97 67
86 66
87 67
96 68
97 69
140117
58 46
59 47
56 34
57 35
86 74
87 75
140139
82 68
83 69
102 98
103 99
84 74

85 75
50 48
51 49
137117
102100
103101
118 40
119 41
44 32
45 33
108106
109107
119 5
84 72
85 73
82 80
83 81
52 44
53 45
108 98
109 99
104100
105101
138137
78 72
79 73
76 70
77 71
52 24
53 25
147120
148121
120 24
121 25
122106
123107
32 2
33 3
6 2
7 3
22 5
114 70
115 71
124 20
23 18
138 28
42 8
43 9
125 19
124 29
114 20
42 19
115 30

20	8
21	9
31	28
139	26
125	27
126	43
127	10
127	30
6	1
7	1
10	1
11	1 TWICE
12	1 TWICE
13	1 TWICE
14	1 TWICE
15	1 TWICE
16	1 TWICE
17	1 TWICE
18	1
20	1
21	1
22	1
26	1
27	1
31	1
34	1
35	1
46	1
47	1
50	1
51	1
76	1
77	1
78	1
79	1
80	1
81	1
88	1
89	1
104	1
105	1
110	1
111	1
116	1
118	1
122	1
123	1
126	1
129	1
133	1
134	1
136	1
144	1

Cost explanation:
 -Runs over 2 weeks
 -175 arcs in solution

147 1
 148 1
 THE TOTAL COST=
 53407

Weekly milage:

$$\frac{53407 - (175 * 150)}{2} = 13579$$

New OFF CW:

Data set.

Frequency based on 8 week rate.

41.07	95.54	1	OFF/C-7	1	OFFUTT
37.37	97.16	8	IAB/C-22	2-9	MCCONNELL
38.32	89.51	8	BLV/C-23	10-17	SCOTT
43.34	96.44	4	FSD-86	18-21	SIOUX FALLS
42.24	96.23	4	SUX-87	22-25	SIOUX CITY
39.22	94.54	4	FLV-88	26-29	FT LEAVENWORTH
39.03	96.46	4	FRI-89	30-33	FT RILEY
38.51	94.33	4	GVW-90	34-37	KANSAS CITY
38.57	95.39	4	FOE-91	38-41	FORBES
37.44	92.08	4	TBN-92	42-45	FORNEY
38.44	93.33	8	SZL-94	46-53	WHITEMAN
38.34	90.09	16	CPS-95	54-69	E ST LOUIS
48.24	101.21	8	MIB-55	70-77	MINOT
47.57	97.24	8	RDR-56	78-85	GRAND FORKS
49.54	97.14	1	YWG-61	86	WINNEPEG
39.46	104.53	8	DEN/C-6	87-94	DENVER
41.09	104.49	8	CYS-53	95-102	CHEYENNE
44.08	103.06	8	RCA-54	103-110	ELLSWORTH
45.48	108.32	4	BIL-59	111-114	BILLINGS
41.32	93.39	4	DSM-81	115-118	DES MOINES
44.53	93.13	4	MSP-85	119-122	MINNEAPOLIS

New OFF output file:

ARCS IN THE SOLUTION

86 70
 86 78
 111 71
 112 72
 113 73
 114 74
 79 71
 80 72
 81 73
 82 74
 83 75
 84 76
 85 77
 95 87
 96 88
 97 89
 98 90

99 91
100 92
101 93
102 94
111103
112104
113105
114106
54 10
55 11
56 12
57 13
58 14
59 15
60 16
61 17
107 70
108 75
109 76
110 77
42 10
43 11
44 12
45 13
119 78
120 83
121 84
122 85
46 42
47 43
48 44
49 45
58 50
59 51
60 52
61 53
46 34
47 35
48 36
49 37
30 2
31 3
32 4
33 5
87 2
88 3
89 4
90 5
91 6
92 7
93 8
94 9
38 6

39	7	
40	8	
41	9	
108	18	
109	19	
110	20	
34	26	
35	27	
36	28	
37	29	
115	14	
116	15	
117	16	
118	17	
95	21	
22	21	
96	23	
97	24	
98	25	
18	1	
19	1	
20	1	
22	1	
23	1	
24	1	
25	1	
26	1	
27	1	
28	1	
29	1	
30	1	
31	1	
32	1	
33	1	
38	1	
39	1	
40	1	
41	1	
50	1	
51	1	
52	1	
53	1	
54	1	
55	1	
56	1	
57	1	
62	1	TWICE
63	1	TWICE
64	1	TWICE
65	1	TWICE
66	1	TWICE
67	1	TWICE
68	1	TWICE

69 1 TWICE
 79 1
 80 1
 81 1
 82 1
 99 1
 100 1
 101 1
 102 1
 103 1
 104 1
 105 1
 106 1
 107 1
 115 1
 116 1
 117 1
 118 1
 119 1
 120 1
 121 1
 122 1

THE TOTAL COST=
 58931

Cost explanation:

-Runs over 8 weeks

-153 arcs in solution

Weekly milage =

$$\frac{58931 - (153 \times 150)}{8} = 4498$$

 5 Depot Summary:

6 depot weekly milage	27467
minus old FFO, OFF, and BWI	-1665
	-4351
	-8071
plus new OFF and BWI	+4498
	<u>+13579</u>
5 depot weekly milage	31457

Yearly Milage:
 1,635,764

Depot Closure Resequenece Computations

11 Depot Weekly Milage.	24070
Close RME and old NZW routes	-799
	-1302
Add enlarged NZW routes (7 dep)	+2365
10 Depot Weekly milage	24334
Recommended <u>10 Depot</u> yearly milage	1,265,368
(additional miles = 13728)	

Recommended 10 Depot Weekly Milage	24334
Close NZY and old SUU routes	-1148
	-4504
Add enlarged SUU routes (10 dep)	+6119
9 Depot Weekly milage	24801
Recommended <u>9 Depot</u> yearly milage	1,289,652
(additional miles = 24284)	

Recommended 9 Depot Weekly Milage	24801
Close CHS and old BWI routes	-487
	-3638
Add enlarged BWI routes (8 dep)	+4665
8 Depot Weekly milage	25341
Recommended <u>8 Depot</u> yearly milage	1,317,732
(additional miles = 28080)	

Recommended 8 Depot Weekly Milage	25341
Close NZW and old BWI routes	-2365
	-4665
Add enlarged BWI routes (6 dep)	+8071
7 Depot Weekly milage	26382
Recommended <u>7 Depot</u> yearly milage	1,371,864
(additional miles = 54132)	

Recommended 7 Depot Weekly Milage	26382
Close LRF and old NIP routes	-800
	-3625
Add enlarged NIP routes (9 dep)	+5510
6 Depot Weekly milage	27467
Recommended <u>6 Depot</u> yearly milage	1,428,284
(additional miles = 56420)	

5 Depot recommendation is unchanged:	
Yearly milage	1,635,764
(additional miles = 207,480)	

Appendix F: Near Term Output

MSF:

BWI locations are effectively removed by setting their latitude and longitude equal to that of Baltimore.

BEST WEIGHT= 210625

DEPOTS=

1	2	3	4	5	7	8	9	11	12
EMINATING NODES ON TOP									
INCIDENT NODES BELOW									
3	3	3	3	3	3	3	3	3	3
10	26	100	101	102	103	111	112	113	116
3	3	3	3	3	3	3	3	3	3
117	122	123	124	136	137	138	139	140	141
3	3	3	3	3	9	1	1	9	114
142	143	144	145	146	135	31	34	114	126
126	125	115	115	125	127	11	8	34	32
125	115	120	121	127	119	153	109	32	35
35	9	130	153	131	119	11	2	67	8
33	130	131	154	132	118	148	67	66	99
99	99	104	132	11	32	98	5	45	7
98	104	105	133	147	36	97	45	46	87
87	109	25	108	153	4	40	12	169	160
86	25	108	106	149	40	42	169	160	156
156	160	170	168	167	167	157	151	152	160
157	170	168	167	166	159	151	152	30	155
166	165	151	150	158	31	38	45	48	49
165	27	150	158	69	38	39	48	49	51
51	51	50	106	107	83	82	66	18	78
47	50	52	107	83	82	81	18	78	62
62	62	42	118	129	107	24	12	164	164
68	19	41	129	128	24	96	164	163	28
163	162	29	150	21	21	20	72	7	88
162	29	161	21	93	20	72	71	88	90
88	90	91	89	94	92	95	2	78	65
91	94	89	22	92	95	23	77	65	64
49	72	63	46	15	25	68	80	76	82
14	63	70	15	75	110	80	76	79	84

84	133	67	76	16	74	38	42	43	44
85	134	73	16	74	17	37	43	44	58
58	58	60	57	86	56	56	55	54	53
13	60	57	59	56	61	55	54	53	6

CW:

FFO Data set.

Frequencies based on 2 week rate.

39.50	84.03	1	FFO/C-8	1	WRIGHT-PATTERSON
42.05	87.49	1	NBU/C-24	2	GLENVIEW
38.10	85.44	2	SDF/C-25	3, 4	STANDIFORD
41.32	93.39	1	DSM-81	5	DES MOINES
41.53	91.42	1	CID-82	6	CEDAR RAPIDS
41.26	90.30	1	MLI-83	7	MOLINE
43.57	90.44	1	CMY-84	8	FT MCCOY
44.53	93.13	1	MSP-85	9	MINNEAPOLIS
42.57	87.53	1	MKE-96	10	MILWAUKEE
42.18	85.14	1	BTL-97	11	BATTLE CREEK
41.35	83.48	1	TOL-98	12	TOLEDO
41.01	83.41	1	FDY-99	13	FINDLAY
40.58	85.11	1	FWA-104	14	FT WAYNE
40.38	86.09	1	GUS-105	15	GRISSOM
39.27	87.18	1	HUF-106	16	TERRE HAUTE
40.29	88.55	1	BMI-107	17	BLOOMINGTON IL
39.09	86.37	1	BMG-108	18	BLOOMINGTON IN
39.06	84.25	1	LUK-109	19	CINCINNATI
36.40	87.29	1	HOP-110	20	FT CAMPBELL

FFO output file:

ARCS IN THE SOLUTION

9	8
9	5
6	5
7	6
10	8
17	7
11	2
20	3
18	16
20	16
15	2
12	11
15	14
13	12
19	3
14	4

4	1	Cost explanation:
10	1	-run over 2 weeks
13	1	-22 arcs in solution
17	1	
18	1	Weekly milage =
19	1	
THE TOTAL COST=		$\frac{6194 - (22 \times 150)}{2} = 1447 \text{ sm/wk}$
6194		

Wright-Patt route interpretation (2 week period):

R1: FFO-BMI-MLI-CID-DSM-MSP-CMY-MKE-FFO
 1 17 7 6 5 9 8 10 1

R2: FFO-FDY-TOL-BTL-NBU-GUS-FWA-SDF-FFO
 1 13 12 11 2 15 14 4 1

R3: FFO-BMG-HUF-HOP-SDF-LUK-FFO
 1 18 16 20 3 19 1

 NZY data set.

Frequency based on 2 week rate.

32.41	117.12	1	NZY/C-5	1	NORTH ISLAND
36.14	115.02	1	LSV/C-14	2	NELLIS
33.32	112.23	1	LUF/C-15	3	LUKE
32.50	115.40	1	NJK-45	4	EL CENTRO
32.39	114.36	1	NYL-46	5	YUMA
35.41	117.41	1	NID-47	6	CHINA LAKE
34.17	116.10	1	NXP-48	7	TWENTYNINE PALMS
34.51	116.47	1	DAG-49	8	BARSTOW
34.12	119.12	1	OXR-50	9	OXNARD
34.54	117.52	1	EDW-52	10	EDWARDS
34.43	120.34	2	VBG-51	11,12	VANDENBERG
32.09	110.52	1	DMA-75	13	DAVIS-MONTHAN

NZY output file:

ARCS IN THE SOLUTION

13 3
 6 2
 3 2
 10 6
 11 9
 13 5
 10 8
 8 7
 9 4
 4 1
 5 1
 7 1

Cost explanation
 -run over 2 weeks
 -15 arcs in solution

11 1	Weekly milage =
12 1 TWICE	
THE TOTAL COST=	$\frac{4546-(15*150)}{2} = 1148 \text{ sm/wk}$
4546	

North Island route interpretation (2 week period):

R1: NZY-NYL-DMA-LUF-LSV-NID-EDW-DAG-NXP-NZY
 1 5 13 3 2 6 10 8 7 1

R2: NZY-VBG-OXR-NJK-NZY
 1 11 9 4 1

R3: NZY-VBG-NZY
 1 12 1

SUU data set.

Frequency based on 2 week rate.

38.15	121.55	1	SUU/F-1	1	TRAVIS
38.40	121.23	2	MCC-31	2,3	MCCLELLAN
37.17	120.31	2	MCE-32	4,5	MERCED
36.20	119.57	2	NLC-33	6,7	LEMORE
37.53	121.14	2	SCK-34	8,9	STOCKTON
36.46	119.43	2	FAT-35	10,11	FRESNO
36.35	121.50	2	MRY-36	12,13	MONTEREY
42.09	121.44	1	LMT-37	14	KLAMATH FALLS
39.29	119.46	1	RNO-38	15	RENO
39.24	118.41	1	NFL-39	16	FALLON

SUU output file.

ARCS IN THE SOLUTION

10 6
 11 7
 16 15
 16 14
 10 4
 11 5
 12 6
 13 7
 8 4
 9 5
 15 2
 8 2
 9 3
 3 1
 12 1
 13 1
 14 1

THE TOTAL COST= 4105

Cost explanation:
 -run over 2 weeks
 -17 arcs in solution

Weekly milage =
 $\frac{4105-(17*150)}{2} = 778$

Travis route interpretation (2 week period).

R1: SUU-LMT-NFL-RNO-MCC-SCK-MCE-FAT-NLC-MRY-SUU
1 14 16 15 2 8 4 10 6 12 1

R2: SUU-MCC-SCK-MCE-FAT-NLC-MRY-SUU
1 3 9 5 11 7 13 1

TCM data set.

Frequency based on 2 week period.

47.08	122.28	1	TCM/C-4	1	MCCHORD
46.34	120.32	2	YKM-40	2,3	YAKIMA
47.37	117.31	2	GEG-41	4,5	FAIRCHILD
46.15	119.06	1	PSC-42	6	PASCO
43.33	116.13	1	BOI-43	7	BOISE
43.02	115.52	1	MUO-44	8	MT HOME
40.47	111.58	2	SLC/C-13	9,10	SALT LAKE CITY
47.30	111.11	2	GFA-57	11,12	GREAT FALLS
43.31	112.04	1	IDA-58	13	IDAHO FALLS
45.48	108.32	1	BIL-59	14	BILLINGS
46.36	111.59	1	HLN-60	15	HELENA

TCM output file.

ARCS IN THE SOLUTION

13 9
14 11
14 13
15 12
10 8
10 7
12 4
7 5
8 6
6 2
15 3
2 1
3 1
4 1
5 1
9 1
11 1

Cost explanation:
-run made over 2 weeks
-17 arcs in solution

Weekly milage =

THE TOTAL COST=
6959

$\frac{6959 - (17 * 150)}{2} = 2205$

McChord route interpretation (2 week period).

R1: TCM-SLC-IDA-BIL-GFA-TCM
1 9 13 14 11 1

R2: TCM-YKM-HLN-GFA-GEG-TCM
1 3 15 12 4 1

R3: TCM-GEG-BOI-SLC-MUO-PSC-YKM-TCM
1 5 7 10 8 6 2 1

OFF data set.

Frequency based on 8 week rate.

41.07	95.54	1	OFF/C-7	1	OFFUTT
37.37	97.16	8	IAB/C-22	2-9	MCCONNELL
38.32	89.51	8	BLV/C-23	10-17	SCOTT
43.34	96.44	4	FSD-86	18-21	SIOUX FALLS
42.24	96.23	4	SUX-87	22-25	SIOUX CITY
39.22	94.54	4	FLV-88	26-29	FT LEAVENWORTH
39.03	96.46	4	FRI-89	30-33	FT RILEY
38.51	94.33	4	GVW-90	34-37	KANSAS CITY
38.57	95.39	4	FOE-91	38-41	FORBES
37.44	92.08	4	TBN-92	42-45	FORNEY
38.44	93.33	8	SZL-94	46-53	WHITEMAN
38.34	90.09	16	CPS-95	54-69	E ST LOUIS
48.24	101.21	8	MIB-55	70-77	MINOT
47.57	97.24	8	RDR-56	78-85	GRAND FORKS
49.54	97.14	1	YWG-61	86	WINNEPEG
39.46	104.53	8	DEN/C-6	87-94	DENVER
41.09	104.49	8	CYS-53	95-102	CHEYENNE
44.08	103.06	8	RCA-54	103-110	ELLSWORTH

OFF output file.

ARCS IN THE SOLUTION

86 70
86 78
79 71
80 72
81 73
82 74
83 75
84 76
85 77
95 87
96 88
97 89
98 90
99 91
100 92
101 93
102 94
54 10
55 11
56 12

57 13
58 14
59 15
60 16
61 17
103 70
104 71
105 72
106 73
107 74
108 75
109 76
110 77
42 10
43 11
44 12
45 13
46 42
47 43
48 44
49 45
58 50
59 51
60 52
61 53
78 18
79 19
80 20
81 21
46 34
47 35
48 36
49 37
30 2
31 3
32 4
33 5
87 2
88 3
89 4
90 5
91 6
92 7
93 8
94 9
38 6
39 7
40 8
41 9
34 26
35 27
36 28
37 29

22	18	
23	19	
24	20	
25	21	
14	1	
15	1	
16	1	
17	1	
22	1	
23	1	
24	1	
25	1	
26	1	
27	1	
28	1	
29	1	
30	1	
31	1	
32	1	
33	1	
38	1	
39	1	
40	1	
41	1	
50	1	
51	1	
52	1	
53	1	
54	1	
55	1	
56	1	
57	1	
62	1	TWICE
63	1	TWICE
64	1	TWICE
65	1	TWICE
66	1	TWICE
67	1	TWICE
68	1	TWICE
69	1	TWICE
82	1	
83	1	
84	1	
85	1	
95	1	
96	1	
97	1	
98	1	
99	1	
100	1	
101	1	
102	1	
103	1	

104	1	Cost explanation:
105	1	-run over 8 weeks
106	1	-141 arcs in solution
107	1	
108	1	Weekly milage =
109	1	
110	1	$\frac{54496 - (141 * 150)}{8} = 4168$
THE TOTAL COST=		
54496		

Offutt route interpretation (8 week period).

R1: OFF-SUX-FSD-RDR-YWG-MIB-RCA-OFF
 1 22 18 78 86 70 103 1

R2: OFF-SUX-FSD-RDR-MIB-RCA-OFF
 1 23 19 79 71 104 1
 R3: 1 24 20 80 72 105 1
 R4: 1 25 21 81 73 106 1

R5: OFF-RDR-MIB-RCA-OFF
 1 82 74 107 1
 R6: 1 83 75 108 1
 R7: 1 84 76 109 1
 R8: 1 85 77 110 1

R9: OFF-CYS-LEN-IAB-FRI-OFF
 1 95 87 2 30 1
 R10: 1 96 88 3 31 1
 R11: 1 97 89 4 32 1
 R12: 1 98 90 5 33 1

R13: OFF-CYS-DEN-IAB-FOE-OFF
 1 99 91 6 38 1
 R14: 1 100 92 7 39 1
 R15: 1 101 93 8 40 1
 R16: 1 102 94 9 41 1

R17: OFF-CPS-BLV-TBN-SZL-GVW-FLV-OFF
 1 54 10 42 46 34 26 1
 R18: 1 55 11 43 47 35 27 1
 R19: 1 56 12 44 48 36 28 1
 R20: 1 57 13 45 49 37 29 1

R21: OFF-SZL-CPS-BLV-OFF
 1 50 58 14 1
 R22: 1 51 59 15 1
 R23: 1 52 60 16 1
 R24: 1 53 61 17 1

R25-R32. OFF-CPS-OFF
 1 62-69 1

NZW data set.

Frequency based on weekly rate.

42.09	70.56	1	NZW/C-9	1	BOSTON
41.35	71.25	1	OQU-114	2	QUONSET STATE
41.04	73.42	1	HPN-115	3	WHITE PLAINS
42.45	73.48	1	ALB-118	4	ALBANY
42.11	72.31	1	CEF-119	5	WESTOVER
40.44	73.25	1	FRG-120	6	FARMINGTON
41.30	74.06	1	SWF-121	7	STEWART
41.16	72.53	1	HVN-125	8	NEW HAVEN
41.19	72.02	1	GON-126	9	GROTON
41.56	72.41	1	BDL-127	10	BRADLEY
42.56	71.26	1	MHT-130	11	MANCHESTER
43.04	70.49	1	PSM-131	12	PEASE
43.53	69.56	1	NHZ-132	13	BRUNSWICK
44.48	68.50	1	BGR-133	14	BANGOR
46.57	67.53	1	LIZ-134	15	LORING
41.40	70.31	1	FMH-135	16	OTIS
44.39	73.28	1	PBG-128	17	PLATTSBURGH
44.28	73.09	1	BTV-129	18	BURLINGTON

NZW output file.

ARCS IN THE SOLUTION

15 14

18 17

6 3

7 3

17 15

14 13

7 4

8 6

10 4

9 8

10 5

13 12

18 11

9 2

16 2

5 1

11 1

12 1

16 1

THE TOTAL COST=
4290

Cost explanation:

-run made over 1 week

-19 arcs in solution

Weekly milage =

4290-(19*150) = 1440

Boston (South Weymouth) route interpretation (1 week period)

R1: NZW-PSM-NHZ-BGR-LIZ-PBG-BTV-MHT-NZW

1 12 13 14 15 17 18 11 1

R2: NZW-FMH-OQU-GON-HVN-FRG-HPN-SWF-ALB-BDL-CEF-NZW

1 16 2 9 8 6 3 7 4 10 5 1

BWI data set.

Frequency based on 2 week rate.

39.11	76.40	1	BWI/F-3	1	BALTIMORE
39.50	84.03	12	FFO/C-8	2-13	WRIGHT-PATT
36.56	76.17	2	NGU/C-10	14,15	NORFOLK
43.14	75.24	2	RME/C-26	16,17	GRIFFISS
41.25	81.51	1	CLE-100	18	CLEVELAND
40.29	80.14	1	PIT-101	19	PITTSBURGH
39.49	82.56	1	LCK-102	20	COLUMBUS
40.49	82.30	1	MFD-103	21	MANSFIELD
35.24	86.05	1	TUH-111	22	TULLAHOMA
35.49	84.00	1	TYS-112	23	KNOXVILLE
38.22	81.36	1	CRW-113	24	CHARLESTON WV
43.07	76.06	2	SYR-116	25,26	SYRACUSE
44.03	75.44	2	GTB-117	27,28	WHEELER SACK
42.12	75.59	2	BGM-122	29,30	BINGHAMTON
42.56	78.44	2	BUF-123	31,32	BUFFALO
43.07	77.40	2	ROC-124	33,34	ROCHESTER
37.05	76.21	12	LFI-136	35-46	LANGLEY
34.40	86.41	4	HUA-137	47-50	HUNTSVILLE
38.08	78.27	2	CHO-138	51,52	CHARLOTTESVILLE
38.17	76.24	2	NHK-139	53,54	PATUXENT
38.15	78.53	2	SHD-140	55,56	SHENENDOAH
37.19	79.58	2	ROA-141	57,58	ROANOKE
39.38	79.54	2	MGW-142	59,60	MORGANTOWN
39.42	77.43	2	HGR-143	61,62	HAGERSTOWN
40.51	77.51	2	UNV-144	63,64	STATE COLLEGE
41.20	75.43	2	AVP-145	65,66	WILKES-BARRE
40.11	76.45	2	MDT-146	67,68	HARRISBURG
34.54	76.53	2	NKT-171	69,70	CHERRY POINT
34.43	77.26	2	NCA-172	71,72	JACKSONVILLE
34.54	82.13	2	GSP-173	73,74	GREENSVILLE
35.26	82.32	2	AVL-174	75,76	ASHEVILLE
36.29	82.25	2	TRI-175	77,78	BRISTOL
37.31	77.19	2	RIC-176	79,80	RICHMOND
35.20	77.58	2	GSB-177	81,82	GOLDSBORO
35.10	79.01	2	POB-178	83,84	POPE
35.13	80.56	2	CLT-179	85,86	CHARLOTTE
36.06	79.56	2	GSO-180	87,88	GREENSBORO
35.53	78.47	2	RDU-181	89,90	RALIEGH

BWI output file.

ARCS IN THE SOLUTION

47 22
47 23
75 48

76 49
73 48
74 49
77 23
78 50
85 73
86 74
22 2
50 3
21 2
71 69
72 70
27 16
28 17
85 83
86 84
18 3
27 25
28 26
87 75
88 76
81 71
82 72
20 18
24 4
33 31
34 32
89 81
90 82
33 16
34 17
29 25
30 26
19 4
57 24
89 58
59 5
60 6
58 5
31 7
32 8
69 14
70 15
35 15
57 55
90 6
56 9
55 51
56 52
63 19
79 36
80 37
64 9

65 63
 66 64
 79 52
 67 66
 53 37
 54 38
 61 10
 62 11
 80 10
 38 11
 39 12
 40 13
 68 12
 7 1
 8 1
 13 1
 14 1
 20 1
 21 1
 29 1
 30 1
 35 1
 36 1
 39 1
 40 1
 41 1 TWICE
 42 1 TWICE
 43 1 TWICE
 44 1 TWICE
 45 1 TWICE
 46 1 TWICE
 51 1
 53 1
 54 1
 59 1
 60 1
 61 1
 62 1
 65 1
 67 1
 68 1
 77 1
 78 1
 83 1
 84 1
 87 1
 88 1

Cost explanation:
 -run over 2 weeks
 -109 arcs in solution

Weekly milage =

$$\frac{35495 - (109 \times 150)}{2} = 9572$$

THE TOTAL COST=
 35495

Baltimore route interpretation (2 week period).

R1: BWI-TRI-TYS-HUA-TUH-FFO-MFD-BWI
 1 77 23 47 22 2 21 1
 R2: BWI-BGM-SYR-GTE-RME-ROC-BUF-FFO-BWI
 1 30 26 28 17 34 32 8 1
 R3: BWI-BGM-SYR-GTB-RME-ROC-BUF-FFO-BWI
 1 29 25 27 16 33 31 7 1
 R4: BWI-NGK-LFI-FFO-HGR-BWI
 1 54 38 11 62 1
 R5: BWI-LFI-FFO-MDT-BWI
 1 39 12 68 1
 R6: BWI-LFI-FFO-BWI
 1 40 13 1
 R7: BWI-GSO-AVL-HUA-GSP-CLT-POB-BWI
 1 87 75 48 73 85 83 1
 R8: BWI-GSO-AVL-HUA-GSP-CLT-POB-BWI
 1 88 76 49 74 86 84 1
 R9: BWI-TRI-HUA-FFO-CLE-LCK-BWI
 1 78 50 3 18 20 1
 R10: BWI-MGW-FFO-ROA-RDU-GSB-NCA-NKT-NGU-BWI
 1 59 5 58 89 81 71 69 14 1
 R11: BWI-MGW-FFO-RDU-GSB-NCA-NKT-NGU-LFI-BWI
 1 60 6 90 82 72 70 15 35 1
 R12: BWI-AVP-UNV-PIT-FFO-CRW-ROA-SHD-CHO-BWI
 1 65 63 19 4 24 57 55 51 1
 R13: BWI-MDT-AVP-UNV-FFO-SHD-CHO-RIC-LFI-BWI
 1 67 66 64 9 56 52 79 36 1
 R14: BWI-HGR-FFO-RIC-LFI-NHK-BWI
 1 61 10 80 37 53 1
 R15-R20: BWI-LFI-BWI
 1 41-46 1

NIP data set.

Frequency based on 2 week rate.

30.14	81.41	1	NIP/C-12	1	JACKSONVILLE
29.50	90.01	1	NBG/C-27	2	NEW ORLEANS
27.50	82.31	2	MCF/C-28	3,4	MACDILL

25.29	80.23	2	HST/C-29	5,6	HOMESTEAD
33.54	84.31	2	NCQ/C-30	7,8	DOBBINS
32.19	90.05	1	JAN-69	9	JACKSON
33.39	88.27	2	CBM-150	10,11	COLUMBUS
33.33	86.45	2	BHM-151	12,13	BIRMINGHAM
33.35	85.51	2	ANB-152	14,15	ANNISTON
32.38	83.35	2	WRB-155	16,17	ROBINS
32.20	84.59	2	LSF-156	18,19	LAWSON
32.22	86.21	2	MXF-157	20,21	MAXWELL
32.20	88.44	2	MEI-158	22,23	MERIDIAN
31.16	85.42	2	OZR-159	24,25	FT RUCKER
31.32	84.12	2	ABY-160	26,27	ALBANY
24.35	81.41	2	NOX-161	28,29	KEY WEST
26.41	80.06	2	PBI-162	30,31	PALM BEACH
28.14	80.36	2	COF-163	32,33	PATRICK
28.25	81.19	2	MCO-164	34,35	ORLANDO
30.24	88.55	2	BIX-165	36,37	KEESLER
30.21	87.19	2	NPA-166	38,39	PENSACOLA
30.29	86.31	2	VPS-167	40,41	EGLIN
30.04	85.34	2	PAM-168	42,43	TYNDALL
30.58	83.11	1	VAD-169	44	MOODY
30.23	84.21	1	TLH-170	45	TALLAHASSEE
34.54	92.08	1	LRF/C-20	46	LITTLE ROCK
35.02	89.58	1	MEM/C-21	47	MEMPHIS
32.30	93.40	2	BAD-63	48,49	BARKSDALE
31.19	92.32	1	AEX-70	50	ENGLAND
35.20	94.22	1	FSM-71	51	FT SMITH
34.29	93.06	1	HOT-72	52	HOT SPRINGS
35.58	89.57	2	BYH-93	53,54	BLYTHEVILLE

NIP output file.

ARCS IN THE SOLUTION

52 51
 51 46
 52 48
 50 49
 53 47
 49 47
 54 10
 54 9
 22 9
 36 2
 23 11
 23 2
 37 22
 12 10
 13 11
 38 36
 14 13
 40 39
 20 15
 15 7

30	5
31	6
39	20
24	21
21	18
40	25
41	24
42	41
18	8
19	7
16	8
43	25
45	42
32	30
33	31
5	3
6	4
26	16
27	17
34	32
35	33
44	27
44	3
4	1
12	1
14	1
17	1
19	1
26	1
28	1 TWICE
29	1 TWICE
34	1
35	1
37	1
38	1
43	1
45	1
46	1
48	1
50	1
53	1

THE TOTAL COST=
19155

Cost explanation:

-run over 2 weeks.

-63 arcs in solution

Weekly cost =

$\frac{19155 - (63 * 150)}{2} = 4853$

The routes of SKF and CHS are identical to the 11 depot model in Appendix E (page 114). The route interpretations are also provided there.

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